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THE TOTAL SOLAR RADIATION DURING THE ANNULAR ECLIPSE ON APRIL 17, 1912

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SCHEME OF THE INVESTIGATION

The annular eclipse of the sun on April 17, 1912, offered a rare opportunity for investigating the total amount of radiation due to the entire "solar atmosphere," i.e., to the complex of layers of the sun lying outside the level generally indicated as the surface of the photosphere.

Every part of the solar atmosphere emits some proper radiation and scatters some photospheric light, and it is only natural to suppose that the lowest layers bear the greatest share in that radiation and scattering. Now, at a total eclipse the base of the atmosphere is always wholly or partly screened by the moon; whereas during the annular phase of the eclipse of April 1912 even the lowest strata of the atmosphere all round the disk contributed to the remaining radiation. From the minimum value through which the remaining radiation passes at the instant of centrality one should be able to calculate an upper limit, which the radiation, emitted and scattered by the entire solar atmosphere, certainly does not exceed.

Since a reliable determination of such an upper limit would afford an important criterion for testing fundamental ideas regarding the nature of the photosphere, the principal aim kept in view in devising our actinometric apparatus was that the minimum of

the radiation-curve should come out as sharply and definitely as possible.

On former occasions (during the eclipses of 1901 in Karang Sago, Sumatra, and of 1905 near Burgos) we measured the march of the total radiation by means of a thermopile directly exposed to the sun's rays, without making use of any lenses or mirrors to concentrate the beam. If circumstances had then allowed us to find the true shape of the radiation-curve, it would have been possible to calculate from those data trustworthy values for the radiating power of successive concentric zones of the solar disk.[1] Unfortunately the weather did not favor the Sumatra and Burgos observations; so we desired to make similar observations again. The apparatus had proved satisfactory, and sensitive enough to give measurable indications of heat even during totality; for at Burgos a break in the clouds had permitted us to state that at mid-eclipse the unscreened part of the corona radiated less than 1/200,000 of the output of the uneclipsed sun or 2/5 of that of the full moon.[2]

For observing the radiation during the annular eclipse we therefore decided to follow substantially the same plan, though with some alterations in the apparatus. This time the minimum would not be so low. From a close discussion of the Burgos results we presumed it to lie somewhere between 1/10,000 and 1/1000. So the galvanometer could be taken less sensitive, but, on the other hand, the steadiness of the zero could be improved and the period of oscillation shortened.

Quickness of indication was, indeed, a very important condition, which not only the galvanometer but also the recipient of the radiation had to satisfy, if the minimum were to be observed exactly.

At the observing station near Maastricht,[3] selected by the

[1] W. H. Julius, "A New Method for Determining the Rate of Decrease of the Radiating Power from the Center toward the Limb of the Solar Disk," *Astrophysical Journal*, **23**, 312, 1906.

[2] *Proc. Roy. Acad. Amst.*, **8**, 503, 1905.

[3] A preliminary account of the observations made by the Netherlands Expedition on April 17, 1912, is to be found in *Proc. Roy. Acad. Amst.*, **14**, 1195, meeting of April 26, 1912. Cf. also: Nyland, "De eklips van 17 April 1912." *Hemel en Dampkring*, **10**, 1, May 1912.

Eclipse Commission of the Royal Academy of Amsterdam, the annular phase of the eclipse was expected to last less than one second.[1] Our thermopile, used in Sumatra and Burgos, required 10 seconds for reaching a stationary temperature after being suddenly exposed to a constant source of radiation, and therefore would be too slow to catch the minimum, although quick enough to give the greater part of the radiation-curve with sufficient accuracy.

DESCRIPTION OF APPARATUS

We determined on arranging two separate equipments: a rapidly working one, and a slower one, both suited for measuring the intensity of radiation from the first until the fourth contact, but in some respects complementing each other. The slower set of apparatus consisted of a thermopile (the same as used before), a Siemens & Halske moving-coil galvanometer with accessories and suitable resistances. The thermopile was very carefully protected against all disturbing influences; it reacted only upon the radiation that passed through a long tube fitted with diaphragms and mounted parallactically, so as to be easily kept pointing toward the sun by means of a finding arrangement.[2] We had ascertained by a special inquiry, that for temperature differences between the solderings not greater than those produced by full sunshine, the electromotive force of the thermopile could be considered strictly proportional to the intensity of irradiation. The deflections of the Siemens & Halske galvanometer were observed visually by examining the positions of a bright index on a transparent scale. With a permanent shunt of 16 ohms the instrument was just deadbeat; one millimeter deflection then corresponded to 10^{-8} amp. The deflections were proportional to the current. The observer had the resistance box close at hand, in order to keep the image on the scale, and marked the epoch of each reading by means of a double-handed chronometer, one hand of which could be stopped and made to catch up again (a *chronographe rattrapante*). Many readings were also made, in the course of the eclipse,

[1] According to J. Weeder, *Proc. Roy. Acad. Amst.*, **14**, 947, 1912.

[2] A description of the instrument is given in *Total Eclipse of the Sun, May 18, 1901; Reports on the Dutch Expedition to Karang Sago, Sumatra*, No. 4: "Heat Radiation of the Sun during the Eclipse," by W. H. Julius (1905).

with the thermopile screened; the zero proved very satisfactorily constant.[1]

Our second actinometric set was especially intended to answer rapidly and to give a photographic record of the middle part of the radiation-curve. It included a bolometer and a galvanometer with a moving coil of extremely small moment of inertia. Both instruments have been designed and constructed by Dr. W. J. H. Moll, who also was in charge of this equipment on eclipse day. The bolometer consisted of many strips of very thin platinum (Wollaston sheet) coated with lampblack, and mounted so as to form two equal gratings, one of which received the radiation. A thick copper frame warranted quick equalization of temperature of all screened parts, while an envelope of nonconducting material protected it against rapid external changes. The whole was fastened to the end of a tube with diaphragms, which was directed toward the sun by an assistant.

As will appear from the photographic records, the galvanometer answered the purpose admirably (time of deadbeat swing less than one second; deflection 4 mm for 1 microvolt; zero steady within 0.1 mm); but the instrument being only a temporary one, adapted to the requirements of this eclipse and not yet to general use, Dr. Moll, who has since been improving the pattern, desires to publish full particulars at a later date.

In order to obtain reasonable bridge-currents within the very wide range of sensitivity imposed by the phenomenon, the observer varied the resistance of the principal bolometer circuit by steps, as the eclipse proceeded, and each time read the strength of the main current on a milliammeter, the resistance in the bridge being left unaltered. That the zero-reading of the sensitive galvanometer was very little influenced thereby was a proof of the symmetry of the arrangement.

OBSERVATIONS MADE WITH THE BOLOMETER

During the greater part of the eclipse the galvanometer deflections were only visually observed, by noticing the motion of the reflected image of a slit on a transparent scale; but from 5 minutes

[1] I am very much indebted to Professor J. J. A. Muller for his valuable assistance in manipulating the thermopile on eclipse day.

PLATE X

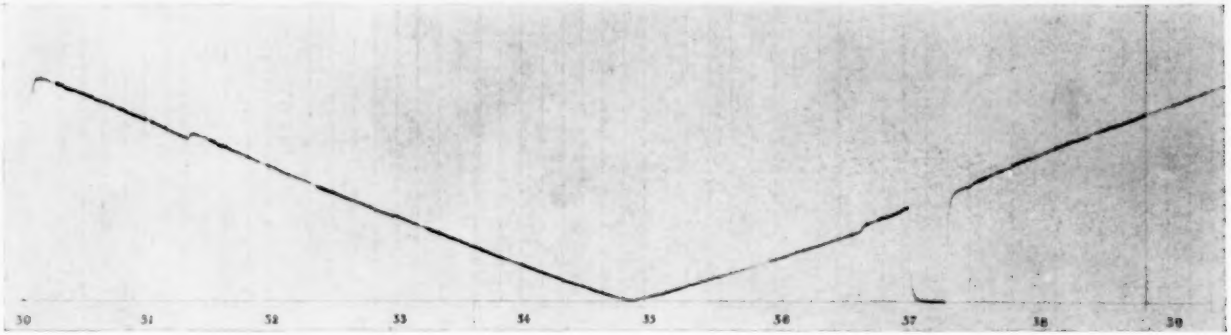

FIG. 1

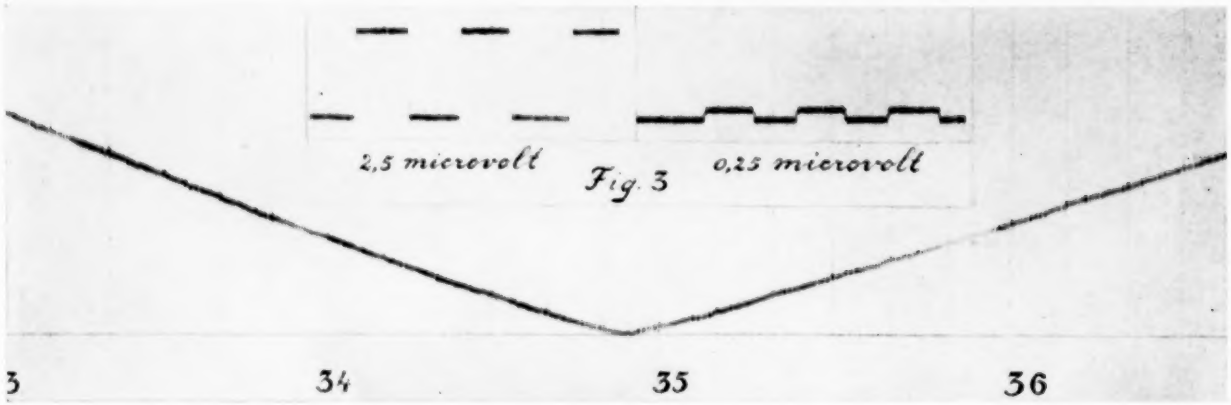

FIG. 2

FIG. 1.—Photographic record of the total solar radiation during $9\frac{1}{2}$ minutes, comprising the annular phase of the eclipse of the sun on April 17, 1912, as obtained near Maastricht with a bolometric arrangement ($\frac{4}{10}$ original size).

FIG. 2.—Middle part of the curve of Fig. 1 ($\frac{8}{7}$ original size).

FIG. 3.—Check of galvanometer condition on eclipse day.

before until 5 minutes after centrality the image was received on a photographic recording drum.

On Plate X, Fig. 1, the photogram is reproduced 9/20 true size. Fig. 2 is the central part of it, 5/4 true size,[1] and Fig. 3 gives on the same scale a control of the volt-sensitivity of the galvanometer, effected immediately after the eclipse was over. It shows well the qualities of the instrument.

The vertical lines are time-signals, produced by a small electric lamp flashing up at intervals of ten seconds in front of the slit of the recording apparatus; the first line following the minimum of the curve corresponds to $0^h34^m57^s$ Leiden M.T.

Two of the zero-readings, obtained by screening the bolometer, are visible on the curve (Fig. 1), one at 0^h30^m, another at 0^h37^m. A straight line joining them may quite safely be taken to represent the zero during the interval. The ordinate of the minimum thus comes out to be a quarter of a millimeter. At 11^h30^m (6 minutes after first contact) a deflection of 6.1 mm was observed visually,[2] the intensity of the main current at that time being 1/195 of its value at the time of recording. Reduced to the latter value of the main current, the deflection corresponding to full sunshine would have been more than $195 \times 6.1 = 1190$ mm, or nearly 5000 times the deflection at minimum.

A few irregularities in the curve, especially at $0^h31^m20^s$ and at $0^h36^m40^s$, require explanation. They are not genuine, but simply due to an excusable negligence of the assistant who had to point the bolometer at the sun. The emotions of the event making him forget to keep the tube continuously in the right direction, he had twice suddenly to make up for the loss. Fortunately the minimum is unaffected.

DISCUSSION OF THE BOLOMETER RESULTS

If the apparatus had followed the radiation instantaneously, the minimum would have been lower yet. We may therefore

[1] The striped aspect of the curve is connected with the click of the recording apparatus.

[2] As a basis for calculation we purposely select this *small* deflection, because the great deflections of the provisory galvanometer were not strictly proportional to the current.

certainly conclude from these observations that at the central phase of the annular eclipse the solar radiation fell below 1/5000 of its ordinary value.

This remainder must in part be due to the unscreened ring of the disk. Assuming the apparent surface of that photospheric ring to be 1/2500 of the surface of the disk (which certainly is a low estimate), and its apparent radiating power per unit of disk-surface to be 1/4 of the average intrinsic radiating power of the disk, we may say that at the epoch of centrality the photosphere was still able to furnish us with at least 1/10,000 of the ordinary amount of radiation.

Consequently, less—and probably much less—than 1/10,000 of the sun's total radiation toward the earth is left as proceeding from the annular part of the *solar atmosphere* visible round the moon's edge.

So far, the inference is pretty sure, because it depends on the outcome of direct observations only.

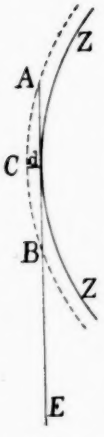

FIG. 1

What we want to deduce next, however, is an estimate of the radiation due to the entire solar atmosphere —or rather to the visible half of it. This we cannot do without making some simplifying assumptions concerning the absolutely unknown conditions prevailing in the sun.

Let *ZZ* (Fig. 1) be the photosphere (with radius r), *ABE* the direction toward the earth. If the radiating and scattering power of the solar atmosphere were distributed homogeneously through its whole depth d, the emission due to the hemispherical shell would bear approximately the same ratio to the atmospheric emission observed at mid-eclipse that the volume of the hemispherical shell ($2\pi r^2 . d$) bears to the volume of the ring produced by the rotation of the segment *ABC* about the sun's diameter, that is parallel to *AB*, ($2\pi r \times$ segment *ABC*).

That proportion is

$$p = \frac{rd}{\text{segment } ABC} .$$

For small values of d the surface of the segment is nearly $2/3\ d \cdot AB$, and the ratio becomes

$$p = \frac{3}{2}\ \frac{r}{AB}\,.$$

Suppose we may replace the actual heterogeneous atmosphere by an ideal homogeneous one for which $d = 2000$ km ($1/350$ of the sun's radius). The corresponding value of AB is about $0.15\ r$, giving for the ratio

$$p = \frac{3}{2}\ \frac{r}{0.15r} = 10\,.$$

Our conclusion therefore is that less than $1/1000$ of the sun's total radiation is emitted or scattered by parts of the celestial body lying outside the photospheric surface.

Even though we are free to admit an uncertainty of several hundred per cent in some of the estimates on which the above calculation is based, our result yet makes it impossible to maintain the current ideas on the nature of the photosphere.

Most solar theories, indeed, consider the photosphere to be a layer of incandescent clouds, whose decrease of luminosity from the center toward the limb of the solar disk would be caused by absorption and scattering of light in an enveloping atmosphere ("the dusky veil"). According to calculations made by Pickering, Wilson, Schuster, Vogel, v. Seeliger, and others, such an atmosphere should intercept an important fraction ($\frac{3}{4}$ to $\frac{1}{3}$) of the photospheric radiation. The atmosphere is of course in a stationary condition; receipts and expenses must balance each other. Now, what would become of that immense quantity of absorbed energy, of which only something of the order of magnitude $1/1000$ is emitted and scattered? So long as we have no evidence of any other form of solar output, especially proceeding from the atmospheric layers, and comparable in magnitude with the sun's total radiation, we are forced to reject the cloud-theory of the photosphere.

The radial variation of the brightness of the disk depends on the nature of the photosphere itself, not of its envelope. A new interpretation of the photosphere, agreeing with this result, will be proposed in a subsequent paper.

OBSERVATIONS MADE WITH THE THERMOPILE

We now proceed to the discussion of the observations made for finding the shape of the entire radiation-curve. In this part of the work our thermopile arrangement had the advantage of the bolometric apparatus in point of proportionality, within wide limits, between radiation and galvanometer deflection.

The total resistance of the thermopile circuit had to be varied in a few steps from 1300 for full sunshine to 100 for the central quarter of an hour, and back again. Table I contains the deflections, all reduced to the lowest value of the resistance, and reckoned

TABLE I

Leiden Mean Time	Intensity of Radiation	Leiden Mean Time	Intensity of Radiation	Leiden Mean Time	Intensity of Radiation
$23^h12^m\ 23^s$...	4960	$0^h21^m\ 23^s$...	849	$0^h44^m\ 54^s$...	612
13 52 ...	(1st contact)	23 42 ...	680	46 37 ...	733
15 35 ...	4950	25 3 ...	593	47 36 ...	805
23 5 ...	4725	28 1.4..	410	48 37 ...	872
25 16 ...	4625	28 34.6..	375	49 43 ...	945
28 2 ...	4460	29 10.4..	335	50 22 ...	993
29 40 ...	4360	30 50.6..	224	50 56 ...	1034
31 28 ...	4280	31 28.4..	183	54 2 ...	1222
37 15 ...	3950	31 57.0..	153	55 16 ...	1313
38 52 ...	3880	32 27.2..	122	55 58 ...	1386
40 27 ...	3765	33 5.8..	87	56 53 ...	1453
46 23 ...	3355	33 28.0..	66.5	57 50 ...	1550
48 31 ...	3170	33 52.6..	46	58 55 ...	1640
50 20 ...	3150	34 23.4..	21	59 57 ...	1738
51 43 ...	3075	(Minimum)..	2.5	1 1 8 ...	1839
0 3 36 ...	2213	35 16.2..	20	3 16 ...	1962
5 8 ...	2075	35 52.0..	50	4 17 ...	2010
6 41 ...	1954	36 14.6..	70	5 38 ...	2095
8 7 ...	1828	36 36.6..	89	6 50 ...	2190
9 45 ...	1685	37 9.2..	119	7 49 ...	2325
11 38 ...	1551	37 40.8..	149	9 9 ...	2382
13 39 ...	1438	38 10.0..	178	38 40 ...	4340
14 53 ...	1342	38 29.7..	198	40 40 ...	4380
16 52 ...	1203	39 7.2..	238	42 10 ...	4425
17 49 ...	1107	39 43.8..	277	44 40 ...	4520
18 38 ...	1054	40 16.8..	317	46 10 ...	4600
19 28 ...	978	40 50.6..	356	52 10 ...	4590
20 8 ...	925	43 56 ...	545	54 10 ...	4660

from zero-positions that were found by interpolation between a series of zero-readings, made in the course of the eclipse with the thermopile shaded. The shift of the zero was small and regular.

Plate XI, Fig. 1 is a reduced copy of the original mapping of

PLATE XI

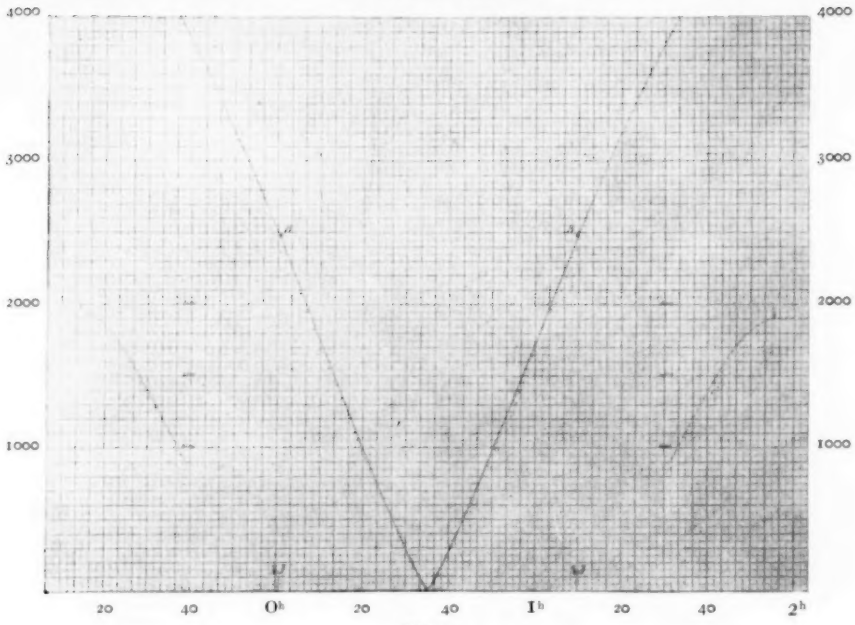

FIG. 1

CURVE SHOWING THE VARIATION OF THE TOTAL SOLAR RADIATION DURING THE ANNULAR ECLIPSE OF THE SUN ON APRIL 17, 1912, FROM MEASUREMENTS MADE WITH A THERMOPILE

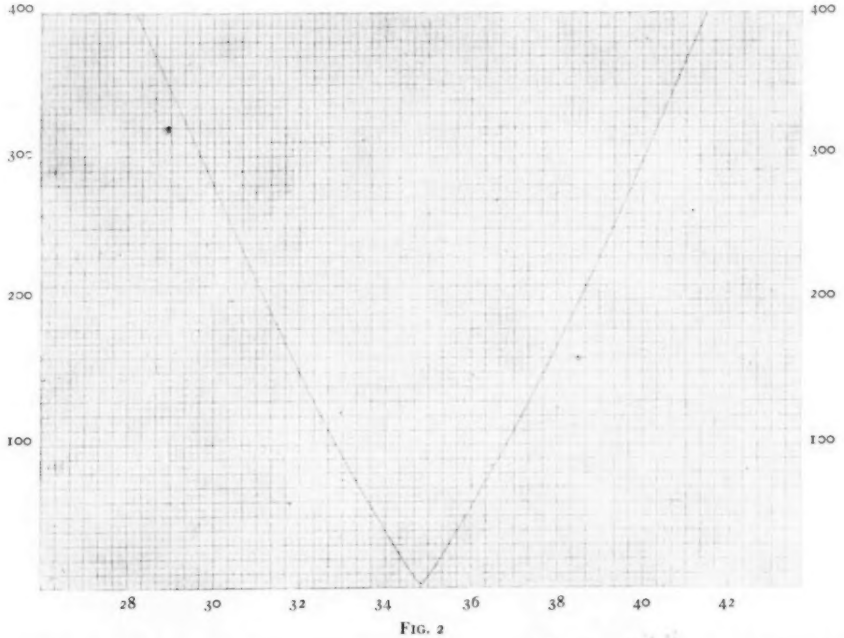

FIG. 2

MIDDLE PART OF THE RADIATION-CURVE ABOVE, ON A TEN TIMES LARGER SCALE

Table I. The deflections observed between $0^h28^m10^s$ and $0^h41^m30^s$, plotted on a ten times larger scale, are shown on Plate XI, Fig 2. These latter observations give evidence of the exceptionally favorable condition of the sky especially during the middle part of the eclipse. When uniting the observational points by a curve, I was quite surprised to find it so perfectly smooth and symmetrical, for in our country a sky without even invisible haze is a rare occurrence.

The central part of this curve corroborates our conclusion drawn from the photographic curve, viz., that the minimum value of the radiation was 1/5000 of the maximum. Indeed, the real minimum value could not be reached by the slow apparatus; but if we prolong the lower parts of the falling and the rising branch of the curve downward as nearly straight lines (beginning at points corresponding to 10 seconds before and 10 seconds after centrality), they meet at *one* millimeter above zero; and according to Plate XI, Fig. 1 the maximum was represented by about 5000 mm.

The rest of the observations ran somewhat less regularly, both in the falling and in the rising phase of the radiation. From notes on sky-condition, made by other members of the party, we could afterward state that the depressions in the series of points exactly corresponded to hazy cloudlets passing before the sun. Yet some arbitrariness was left in the process of tracing the radiation-curve so as to answer to an ideally constant degree of transparency of the sky. We simply made the curve pass through the *highest* points (because the observed values could only be too small), and for the rest took care that the curvature should vary as regularly as possible.

Special attention may be drawn to the points *B* (Plate XI, Fig. 1) marked by small circlets. They are deduced from the Burgos observations of 1905[1] in the following way.

In the course of that eclipse the sun shone sometimes for a few minutes in a beautifully clear patch of sky between heavy clouds, and happened to do so during the phases in which the radiation passed through one-half of its maximum value. The exact epochs at which the intensity was $\frac{1{,}794{,}000}{2} = 897{,}000$ occurred

[1] *Astrophysical Journal*, **23**, 312, 1906.

33^m38^s before second contact and 33^m43^s after third contact; so, on the average, $33\frac{2}{3}$ minutes were required for the moon to cover the second effective half of the solar disk.

Now, at Burgos the moon's edge took $77\frac{3}{4}$ minutes to cross the whole solar disk; at Maastricht, in 1912, it took $80\frac{3}{4}$ minutes. If, therefore, the ratio of the radius of the moon's disk to the radius of the sun's disk had been the same in both cases, then the time necessary for covering the second effective half of the solar disk would have been, at Maastricht, $33\frac{2}{3}\times\frac{80\frac{3}{4}}{77\frac{3}{4}}$ = very nearly 35 minutes.

But at Maastricht the moon's radius was practically equal to the sun's radius, whereas at Burgos the radii were in the proportion 132.8 : 126.8. This difference between the two cases implies that the interval of 35 minutes, calculated for Maastricht, is a little too great. Indeed, when drawing circles representing the sun and the moon in the right proportion and position, and taking the distribution of brightness on the disk into consideration, one easily concludes that the interval has to be taken about 25 seconds smaller, say $34\frac{1}{2}$ minutes.

Consequently, the results obtained in 1905 required that in 1912, at the epochs $0^h0^m20^s$ and $1^h9^m20^s$ (i.e., $34\frac{1}{2}$ minutes before and after centrality), the radiation should have shown half its maximum intensity, or $\frac{4960}{2}=2480$ scale divisions. This is indicated by the points *B*. The agreement with the actual observations of 1912 is indeed very satisfactory.

During the middle phase of the Burgos eclipse the conditions were, on the contrary, so unfavorable that the central part of the radiation-curve, there obtained, claims no confidence.

It was worth while, therefore, to found on our present eclipse-curve a renewed application of the method, formerly devised,[1] of determining the rate of decrease of the radiating power from the center toward the limb of the solar disk.

DISCUSSION OF THE THERMOPILE RESULTS

On a homogeneous piece of paper a circle of 40 cm in diameter, representing the sun, was drawn, and divided in the manner shown

[1] *Ibid.*, **23**, 312, 1906.

by the adjoined figure.[1] There are concentric zones, indicated by the numbers 1 to 12, and arcs representing the moon's limb in a series of positions. The width of the sickle-shaped strips bounded by these arcs is 1/20 of the sun's radius, excepting the strips *a*, *b*, *c*, *d*, for which it is 1/40.

FIG. 2

In $40\frac{3}{8}$ minutes the moon's limb accomplished a distance equal to the sun's apparent radius; so the strips *a*, *b*, *c*, *d* required $1/40 \times 40\frac{3}{8}$ minutes each for reappearing from behind the moon, the strips *e* to *u* took $1/20 \times 40\frac{3}{8}$ minutes each. On our curve (Plate XI) we read the successive increments of the radiation, corresponding to the series of sickle-shaped strips. We shall denote these increments by the same letters as the strips.

[1] The figure is not a copy of the original drawing, as this could not be so much reduced on account of the delicacy of the lines.

The increment a is entirely due to radiation from zone 1; the increment b to radiation from the zones 1 and 2, etc.

Let us indicate by x_n the average intensity of the radiation with which a unit of disk-surface, belonging to zone n, supplies our thermopile. Then the increment h, for instance, will be composed as follows:

$$h = \theta_1 x_1 + \theta_2 x_2 + \ldots\ldots + \theta_7 x_7,$$

θ_1, θ_2, etc., being the surfaces of the parts which the corresponding zones contribute to the strip h. Though possible, it is extremely tedious to calculate these surfaces. We therefore determined them

TABLE II

Increments	Coefficients of:											
	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}
a= 47..	251.0	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
b= 53.5	83.0	168.4	.....	.....	.....	.....	.....	.....	.....	.....	.....	.....
c= 58.5	25.5	88.5	137.5	.....	.....	.....	.....	.....	.....	.....	.....	.....
d= 62..	13.8	34.5	78.5	123.0	.....	.....	.....	.....	.....	.....	.....	.....
e=130..	15.7	37.5	59.6	113.0	264.0	.....	.....	.....	.....	.....	.....	.....
f=135..	10.9	21.0	31.1	45.0	163.0	217.0	.....	.....	.....	.....	.....	.....
g=140..	8.5	15.0	19.5	27.0	80.0	146.0	192.0	.....	.....	.....	.....	.....
h=144..	8.1	11.9	15.8	21.1	55.3	77.0	298.0	.....	.....	.....	.....	.....
i=147..	7.7	10.3	12.3	15.9	42.0	55.5	198.0	146.5	.....	.....	.....	.....
j=150..	7.4	9.3	11.0	13.2	33.0	42.0	123.5	247.0	.....	.....	.....	.....
k=152..	7.1	8.4	9.2	11.9	28.7	34.8	93.5	168.5	120.0	.....	.....	.....
l=153..	6.9	8.2	8.8	10.2	25.4	30.2	76.6	108.2	204.2	.....	.....	.....
m=154..	6.9	8.1	8.5	9.8	22.4	27.5	66.0	86.5	142.0	98.2	.....	.....
n=154.5	6.8	8.0	8.3	9.5	20.8	24.9	58.0	73.4	96.4	165.3	.....	.....
o=154..	6.8	7.7	8.1	9.2	19.8	22.6	52.5	63.6	77.8	119.7	77.7	.....
p=154..	6.8	7.6	8.0	9.0	19.1	21.1	49.1	57.3	66.2	82.2	134.0	.....
q=154..	6.7	7.5	7.8	8.8	18.3	19.7	44.9	53.0	57.7	68.9	164.7	.....
r=153.5	6.7	7.4	7.6	8.6	17.6	19.0	42.4	49.7	53.4	60.0	181.2	.....
s=152.5	6.8	7.5	7.6	8.4	17.0	18.2	40.3	45.5	49.2	54.5	143.0	50.3
t=151.5	6.8	7.5	7.5	8.2	16.7	17.5	39.2	42.9	46.5	51.1	115.3	83.6
u=149.5	6.8	7.4	7.5	8.1	16.5	17.1	38.0	41.7	45.1	48.3	102.0	97.0

by cutting out and weighing the pieces of each strip. So the unit of area, adopted for measuring the surfaces, corresponds to a piece of our drawing-paper weighing 1 mg. Expressed in that unit, the coefficients θ_1, θ_2, ... θ_7 were found to be 8.1, 11.9 .... 298.0. Table II contains all the coefficients of x_1, x_2, x_3 .... x_{12} thus obtained. The first column gives the values of the increments of the radiation as read on the eclipse-curve. Every horizontal

row defines an equation. From the first equation we obtain x_1, from the second equation x_2, etc.

The results are collected in the second column of Table III. The third column shows the same values converted into percentages of the intensity prevailing in the center of the disk. After they had

TABLE III

Distance of Zone from Center of Disk	Average Radiating Power per Unit of Zone-Surface			Distance from Center of Disk
	Found Directly from the Equations	Reduced to Value 100 at Center	Found by Graphical Interpolation	
0.9875.....	$x_1 = 0.18725$	48.6	40.0	1.0
0.9625.....	$x_2 = 0.2254$	58.5	61.0	0.95
0.9375.....	$x_3 = 0.2457$	63.9	69.0	0.9
0.9125.....	$x_4 = 0.2631$	68.4	74.2	0.85
0.875.....	$x_5 = 0.2813$	73.0	77.8	0.8
0.825.....	$x_6 = 0.2900$	75.4	80.7	0.75
0.75.....	$x_7 = \{0.3038, 0.3103\} = 0.3071$	79.8	83.3	0.7
0.65.....	$x_8 = \{0.3221, 0.3305\} = 0.3263$	84.8	87.4 91.0	0.6 0.5
0.55.....	$x_9 = \{0.3463, 0.3432\} = 0.3447$	89.5	93.8	0.4
0.45.....	$x_{10} = \{0.3519, 0.3562\} = 0.3540$	92.0	96.5 98.3	0.3 0.2
0.3.....	$x_{11} = \{0.3656, 0.3694, 0.3681, 0.3734\} = 0.3691$	95.9	99.5	0.1
0.125.....	$x_{12} = \{0.3817, 0.3842, 0.3860\} = 0.3840$	99.8	100.0	0.0

been plotted on millimeter paper, a smooth curve was drawn, fitting the points as well as possible. On this "distribution-curve" the numbers of the fourth column were read as ordinates, belonging to the places defined in the fifth column. Our results are thus made more easily comparable with those obtained by other observers.

It is not surprising to find the shape of our distribution-curve sensibly different from the shape of any of the curves that represent Vogel's spectrophotometric measurements. Indeed, the latter show the distributions characteristic of special groups of rays, each covering a narrow part of the spectrum; they are germane, but yet vary considerably with the wave-length. The combined effect of all waves (invisible ones included), that are absorbed by our thermopile, must give a distribution-curve of another type, less simple than that to which Vogel's curves for nearly monochromatic light belong.

SUMMARY

During the annular eclipse of the sun on April 17, 1912, the variation of the total radiation has been observed near Maastricht under exceptionally favorable sky-conditions, with two mutually independent sets of apparatus.

One set, comprising a bolometer and a short-period recording galvanometer, served the purpose of finding as accurately as possible the proportion of the minimum to the maximum radiation.

The ratio was found to be nearly 1/5000. On this result we based an estimate of the total amount of energy radiated and scattered by the entire solar atmosphere; we thus obtained a very small fraction of the solar output (about 1/1000).

It is impossible, therefore, to ascribe the fall of the sun's brightness from the center toward the limb of the disk to absorption or scattering of the light by an atmosphere, enveloping a body that otherwise would appear uniformly luminous. The cloud-theory of the photosphere is not borne out by the facts.

With the other set of apparatus, consisting of a thermopile and accessories, we obtained a sufficient number of reliable readings for constructing the whole radiation-curve, from the first until the fourth contact, with a fair degree of exactness. Besides confirming the value of the minimum as found with the bolometer, this curve procured the data necessary for once more determining the rate of decrease of the radiating power from the center to the limb of the solar disk.

UTRECHT
January 1913

THE VARIATION WITH TEMPERATURE OF THE ELECTRIC FURNACE SPECTRUM OF IRON[1]

By ARTHUR S. KING

It is well known that the spectrum of a given element is usually subject to large variations depending on the physical conditions of the radiating source. The differences between flame, arc, and spark spectra have been studied, with a considerable divergence of opinion among investigators as to how largely these differences may be ascribed to temperature rather than to the electrical and chemical conditions which are manifestly present in different degrees in the several sources. Between the flame and the arc, overlapping in temperature some of the hotter flames, stands the tube resistance furnace, with which the investigation now to be described has been carried out. By the use of this apparatus, any desired steps of temperature may be obtained and measured, up to a point where the vaporization of the carbon tube becomes excessive. The resulting spectra show a progressive change in the relative intensities of lines with increase of temperature. It is the purpose of this paper to give the intensities of iron lines as produced by the furnace at low, medium, and high temperature, and a comparison in some detail with the arc spectrum, together with some mention of the spectra from other sources. The material available shows not only the approximate temperature at which a given line appears in the iron spectrum, but also the rate at which the line strengthens with increasing furnace temperature and with the change from furnace to arc. The classification based on these results will, it is hoped, aid in showing to what extent an observed variation in the spectrum of a given source is to be ascribed to temperature differences.

APPARATUS AND METHODS

1. *The electric furnace.*—A general description of the tube resistance furnace used in the Pasadena laboratory was given in

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 66.

the first publication concerning it.[1] The furnace consists essentially of a tube of Acheson graphite, each end of which is clamped in a contact block which connects it with one of two water-cooled copper pipes leading in the current. The whole is inclosed in a heavy steel cylinder cooled by water-jackets, the electrode tubes passing through one head of the cylinder. Windows in each end allow light from the furnace tube to pass to the spectrograph and also permit of pyrometer measurements.

The contact blocks, instead of being entirely of graphite, as in the original design of the furnace, have been improved by making them of massive blocks of bronze 5 cm thick, sawed from top to bottom, and fitting around the upper or lower electrode tube as the case may be. In the center of each contact block is a cylindrical cavity into which fits a disk of graphite 5 cm in thickness and 7.6 cm in diameter, sawed across the vertical diameter and bored in the center to receive the end of the graphite tube, which is usually about 19 mm outside diameter, 12.5 mm inside diameter, and 30.5 cm long. These contact blocks give little variation in contact resistance, the surfaces being smooth and of large area. The two halves are fastened together by four horizontal bolts and when these bolts are moderately tight the smooth contact surfaces between bronze and graphite allow enough slipping to prevent breaking of the tube through relative expansion of the connections.

In the earlier experiments, the furnace tube was inclosed by a split graphite tube which was surrounded by loose carborundum as heat insulation. In the work done by the writer with the furnace filled with air or carbon dioxide at high pressure[2] such a jacket is almost indispensable on account of the rapid oxidation of the tube, if it is exposed directly to the compressed gas, and the strong convection of heat to the steel walls of the chamber. In comparing the spectra at various furnace temperatures, however, the chamber is regularly pumped out to a pressure of less than

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 28; *Astrophysical Journal*, **28**, 300, 1908.

[2] *Contributions from the Mount Wilson Solar Observatory*, Nos. 53 and 60; *Astrophysical Journal*, **34**, 37, 1911, and **35**, 183, 1912.

2 cm of mercury, and, when this is done, a much greater constancy of temperature is obtained by using no heat jacket. The tube then quickly reaches an equilibrium of temperature, which varies little during the time usually required for a photograph. With the carborundum jacket, on the other hand, the tube temperature increases steadily for some time, on account of the slow heating of the jacket, so that either a reduction of the impressed voltage or occasional breaking of the current for a few seconds is required to prevent too large a temperature variation during the run. Dispensing with the jacket naturally requires a larger current to produce the same temperature of the tube, but if sufficient power is available, the greater constancy of the temperature is a decided advantage.

The 50 K.W. transformer used for the furnace gives a range by 5-volt steps from 5 to 30 volts. For the temperatures employed in these experiments, potentials from 15 to 30 volts were generally used, the currents ranging from 800 to 1600 amperes.

2. *Measurement of temperature.*—Observations with a Wanner pyrometer were taken regularly during the operation of the furnace, the interior of the furnace tube being viewed through the window opposite to that directed toward the spectrograph. This method should give reliable values for the relative temperatures at which spectra were successively obtained, which was the chief object in the present work. The reading necessarily gives a mean value of the temperature from end to end of the tube, assuming that the departure from black-body conditions is not great, since the line of view can be inclined only slightly to the tube's axis, and thus the temperature of any particular part of the tube is uncertain. Attempts have been made to measure the temperature at the center of the tube by placing a graphite plug midway in its length. Readings of the pyrometer when directed at this plug have given temperatures 100° to 150° higher than the mean temperature when viewed without the plug. The temperature of the plug does not correctly give that of the adjacent wall of the tube, but is probably close to it by reason of the high heat conductivity of graphite. It is also an open question how nearly the temperature of metallic vapor inside the tube agrees

with the temperature of the tube itself. These points, however, do not invalidate the relative measures required in this investigation.

3. *Photography of the spectrum.*—Large-scale photographs of furnace spectra have been used as far as possible, having the obvious advantages of avoiding blends and showing more clearly the character and structure of the lines. The vertical Littrow spectrograph described in previous publications[1] was employed, the arrangement most used being with an objective of 30 feet (9.1 m) focus and a Michelson plane grating of 7.2×19 cm ruled surface, of which area only a part about 5×15 cm could be used for the best definition. The dispersion for the first order varied from 1.95 Å. per mm in the blue to 2.06 Å. per mm in the red. The range from λ 3880 to λ 6600 was covered on this scale. A large part of the spectrum, including the portions where lines are most numerous and variable, was later photographed in the second order with a dispersion close to 0.95 Å. per mm. The plates were 9.2×43.2 cm in size, the emulsions most used being the Seed "Gilt Edge 27," the Cramer "Inst. Isochromatic," and the Seed "27" bathed with the Wallace three-dye solution of pinacyanol, pinaverdol, and homocol.[2] Cramer "Crown" plates were also used for some photographs in the blue region.

The spectrum beyond λ 6600 and to the violet of λ 3880 has been photographed with a concave grating spectrograph recently constructed, which gives very bright spectra with excellent definition. Many photographs of the visible region were also taken with this and used chiefly to check the large-scale plates. The grating in this instrument is of 1-meter radius and 5.1×8 cm ruled surface, and was made by J. A. Anderson on the Rowland dividing engine. It is mounted, with slit and camera-box, on a rigid steel frame, inclosed in a light-tight case. As adjusted, the spectral region covered is approximately from λ 2000 to λ 8000 in the first order, a strip of film 38 cm long being used in a metal

[1] Hale, *Contributions from the Mount Wilson Solar Observatory*, No. 27; *Astrophysical Journal*, **28**, 244, 1908; King, *Carnegie Institution of Washington Publication*, No. 153, 13, 1912.

[2] *Astrophysical Journal*, **26**, 299, 1907.

holder. In the work thus far, the regular Eastman kodak film has been used. It is sensitive for strong lines to about λ 5600, with a gradual decrease from the blue to the yellow; but the sensitiveness to the red of λ 5000 is much increased by the three-dye bath, which the films take very satisfactorily. The sharp definition permits the films to be examined under a high magnification, so that a preliminary survey of the ultra-violet in the second order (dispersion 1 mm = 8.5 Å.) was made to good advantage, the first order being used in the extreme ultra-violet on account of its strength. This small spectrograph has been mounted at the end of the furnace opposite to that which is directed at the large Littrow instrument, and simultaneous photographs were frequently taken, giving a long range of spectrum for the same conditions under which a selected region was photographed by the large-scale spectrograph.

4. *Operation of the furnace.*—The furnace having been placed in position, with a quantity of iron filings in the tube, and the current turned on, an image of the interior of the tube was focused on the slit of the spectrograph employed, the focusing lens of glass or quartz being selected of such focal length as to give an image of convenient size on the slit, and at the same time fully to illuminate the grating. The fixed character of all parts of the furnace prevents any change in the illumination of the grating such as often occurs with other sources.

Furnace spectra for two and sometimes three different temperatures were usually taken on the same plate, the exposures being timed so as to give a number of prominent lines about the same intensity in each photograph. Several arc spectra were added with varying exposure times by reflecting the light from an iron arc through the same lens as was used for the furnace exposures. This gave a means of easy identification of the furnace lines together with a number of arc spectra, from which the one whose average intensity was best suited for comparison with the furnace spectra could be selected. Since the first-order spectrum of the 30-ft. (9.1 m) spectrograph gave almost 800 Å. on a single plate, it will be seen that a plate properly exposed furnished a large amount of material in which photographic differences, especially in the

matter of development, did not enter. While special weight was given to a few photographs of exceptional quality, these have been fully checked by other good plates taken with both the large and the small spectrographs, the former including a number of second-order spectra for the detection of possible blends.

Three approximate temperatures were chosen, which will be referred to as low, medium, and high. Pyrometer readings for these, taken in the manner already described, gave values of 1800° to 1900° C. for the low temperature, 2100° to 2300° C. for the medium, and 2500° to 2700° C. for the high temperature. The intensities of lines were estimated on at least three good plates, and frequently more, for each range of temperature, the results being consistent enough to enable one to place pretty definitely the position of a plate on the temperature scale by the relative intensities of certain lines especially sensitive to temperature change.

THE GENERAL PHENOMENA OF VARIATION OF SPECTRA WITH FURNACE TEMPERATURE

The arc spectrum under certain conditions, in general those given by the central region of the arc, not close to either pole, is usually taken as the standard for such substances as can be volatilized to advantage in the arc, by reason of the richness in lines and the approximate constancy of relative intensities in the spectrum thus produced. As compared with the arc spectrum of iron, the furnace spectrum shows marked differences at all stages of temperature. At the lowest temperature at which the vapor radiates, a group of lines appears which includes not only some of the strongest arc lines but also other lines which are only moderately strong and others which are quite faint in the arc. Many very strong arc lines are entirely absent. As the temperature rises, other lines appear, but by no means in the order to be expected from their arc intensities; and by taking a range of temperature such as was used in these experiments it is seen that *the lines grow in intensity with temperature at very different rates*. Part of the lines which appeared at the lowest temperature increase in intensity very slowly, some of them, in reference to the majority of the

lines, actually seeming to weaken slightly at the higher temperatures. Other lines about hold their own, while many of the representative arc lines increase very rapidly in intensity. At the highest furnace temperatures, the furnace spectrum compares closely in richness with that of the arc; in fact, experiments thus far have indicated that it is chiefly a matter of long exposure to bring out practically all of the arc lines in the furnace at high temperature. The differences in relative intensities of lines, however, are still large, with two extreme types. One class includes lines very strong in the arc which are produced faintly only with great difficulty in the furnace. Lines of the other class are strong at all furnace temperatures, and in the arc are of moderate strength, sometimes very weak. Between these extremes there is a large variety in the behavior of the furnace lines which will be made the basis of the classification to be given.

THE STRUCTURE OF FURNACE LINES

In a previous paper by the writer on the pressure-shift of furnace lines,[1] attention was called to the width of the lines in proportion to their density as possibly being connected with their sensitiveness to pressure displacement. This structure has been studied farther in the spectra taken with the furnace *in vacuo* at different temperatures.

The vapor distribution in the furnace differs materially from that in the arc. We have in the furnace tube a very gradual decrease in temperature and vapor density from the middle toward either end. At the lowest temperature for which a spectrum can be obtained, only the vapor in the central portion is hot enough to radiate. The lines are then comparatively narrow, "hard," and can be given any desired blackness in the negative by long exposure. A higher temperature results in vapor nearer the ends of the tube being made hot enough to radiate, and therefore absorb, the central vapor at the same time giving a wider line. The effect of this gradual increase in the absorptive power of the vapor as it nears the end of the tube is to soften the middle of the

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 60; *Astrophysical Journal*, **35**, 183, 1912.

spectrum line and give all variations as the temperature of the tube increases, from a hard, narrow line to complete self-reversal, provided that the rarer vapor near the ends of the tube ever becomes hot enough to radiate (and absorb) the wave-length in question. A short range of spectrum photographed at high temperature will often illustrate the steps in this process by different lines. Those lines which the hottest vapor at the center of the tube is barely able to give are narrow. Other lines not requiring so high a temperature show the gradual widening with softening of the center, through the diffuse stage which precedes reversal, and then clear reversals for such lines as are given by the vapor close to the end. While these conditions for reversal are necessary, they are not always sufficient, since the ease of reversal of iron lines increases toward the violet end of the spectrum and may vary for different lines in other respects which the present investigation has not shown.

INTENSITY SCALE

It would be highly desirable to place the grading of line intensities on a strict photometric basis; but all who have attempted this have met the fundamental difficulty that the increase of width with density as a line strengthens is very different for different lines. A scale of blackness alone (for lines in the negative) would be highly misleading. A scale made by successive photographs of an actual spectrum line whose intensity could be closely controlled and made to increase at a known rate could be used only for a class of lines showing the same behavior as regards the increase of width with density. Even this would involve large errors when the photographic scale was compared with spectrum plates differing in contrast and amount of development, and not always normally exposed. Different scales for sharp and diffuse lines would be quite necessary, and there is a wide variation in each of these classes. Further, the comparison of narrow, dense lines with widely reversed lines would seem to be beyond the reach of such a method.

These difficulties, which are general for emission spectra, are increased when furnace lines for different temperatures are com-

pared. The rapid widening and softening of a line with increased temperature, mentioned in the preceding section, makes it harder to compare with the appearance of the same line at low temperature, where it is narrow and its density is given by long exposure. When, however, the spectrum for a given temperature is considered by itself, it is found quite possible to grade the line intensities in a consistent manner when all features of a given line are considered.

Proceeding in this way in the present work, a line distinctly outlined on the plate has been graded "1," a fainter appearance being indicated by "trace." If, as was usually the case, none of the lines were exposed to reach full blackness in the negative, a grading of intensities for the various lines could be made which would be confirmed with small variations on a second examination of the plate by the same person, and with differences only slightly greater by another observer. The extension of the scale to include reversed lines was not difficult, since the portion of spectrum being studied usually offered lines in various stages preliminary to reversal whose position in the scale between sharp lines and those fully reversed was fairly distinct. The steady character of the furnace radiation and the dependence of a line's intensity on the portion of the tube where the vapor is in a condition to produce the line permit a grading of this kind to be more consistent than is often the case with the arc or spark. The lines for a different furnace temperature are graded in the same way. In the final tabulation, if a line is graded 10 for two temperatures, this does not mean that the line is exactly alike as regards width and density in the two cases, but that it bears the given relation to the lines in its own spectrum for each temperature.

The writer is well aware that personal and photographic differences enter to an undesirable degree in this method of assigning intensities, but where the aim is to tell whether at a certain stage of temperature a line appears on a normally exposed plate and to give its approximate intensity compared with other lines at the same temperature, I believe the method pursued fulfils the requirements better than photometric measures which would require constant modification by a consideration of the general appearance of the spectrum line concerned.

THE TEMPERATURE CLASSIFICATION OF IRON LINES

In pursuance of the object of indicating the relative response to temperature of different lines, both as to the stage of initial appearance and the rate of growth with increase of temperature, six classes have been formed. A reference class is required, which should be made up of a number of lines which are strong at all temperatures and show about the same rate of change. This is the group to be designated as Class I B. They are plentiful throughout the spectrum, except in the orange and red, and the photographs have been made so as to give these lines nearly the same intensity for different temperatures.

Class I A has the distinguishing characteristic of strength at all furnace temperatures after the vapor begins to radiate, and notable weakness in the arc. As compared to the reference group I B, some I A lines show a slight weakening as the temperature increases, but they remain among the stronger furnace lines at the highest temperature. In the arc, however, they are among the weaker lines, sometimes being barely visible in a normally-exposed arc spectrum. Care must be taken to distinguish these from impurity lines which show a similar behavior, the strongest lines of a foreign substance often being given with greater intensity in the furnace than in the arc between iron terminals. To make the identification of the lines of Class I A as certain as possible, all of them have been photographed in the second-order spectrum with a scale of about 0.95 Å. per mm, an arc spectrum being taken on the same plate with the ends of the furnace and arc lines overlapping. The I A lines were found to coincide exactly in every case with faint arc lines which are regularly ascribed to iron in the wave-length tables. Possibly a few of these lines appearing in the iron arc may be shown later to belong to foreign substances, a point which has not been thoroughly investigated in this laboratory, but their regular behavior in the arc and spark is that of weak iron lines, so that the phenomena offered by this important class may be regarded as in all probability real.

Class I B embraces the well-known group of "flame" lines which are given readily in the hotter flames and are relatively strong in the outer envelopes of the iron arc. In the furnace

they are strong at all temperatures, being taken as the reference group in this classification. In the arc they are usually of moderate strength, although those in the green-yellow are among the strongest arc lines. There is usually a clear distinction in the arc between these and the lines of Class I A, for which the arc conditions appear to be distinctly unfavorable.

Class II includes a large number of the stronger arc lines. In the furnace they are distinct, often strong, at the lowest temperature, but as the temperature rises, these lines strengthen much faster than the lines of Class I, and are usually found to have gone up rapidly in the interval between the highest furnace temperature and that of the arc.

Class III lines are absent or faint at the lowest temperature, appear distinctly at medium temperature, show a rapid growth at high temperature, and are strong in the arc. Their rate of growth is similar to the lines of Class II, but they require a higher initial temperature for their production.

Class IV lines appear only at the highest furnace temperature (perhaps as a trace at medium), but show a fair strength. Their arc intensity is usually relatively much greater than in the furnace.

Class V includes lines which are absent or very faint in the furnace, their strength in the arc varying greatly. Experiment has shown that it is possible to bring out many if not all lines of this class by prolonged furnace exposure at high temperature, but the difference between their arc and furnace intensities is greater than for Class IV. In the blue and violet, where impurity lines from several rich spectra are somewhat troublesome, lines entered as "trace" or "1" at high temperature may occasionally belong to foreign substances, as their weakness made them difficult to obtain on the largest-scale plates and hard to measure closely when they did appear. If any of these are not due to iron in the furnace spectrum, the classification would be altered only in a few cases by moving Class IV lines into Class V.

From the furnace material available, it is usually easy to tell in what group of the foregoing classification a line belongs. A few lines are on the border between Classes I A and I B, since

the distinction depends mainly on the arc intensity. A decision between Classes IV and V is sometimes difficult for weak arc lines, but for such lines the difference is not usually important. The distinction is clear and valuable when we have a strong arc line that may be brought out readily (Class IV) or only with great difficulty (Class V) at the highest furnace temperature.

For some purposes a grouping of lines according to the temperature at which they first appear may be useful. In that case, Classes I A, I B, and II may be regarded as low-temperature lines, Class III as belonging to medium, and Classes IV and V to high temperature. This grouping leaves out of account the rate of increase with temperature, to show which is one of the main objects of the present work.

THE DETECTION OF BLENDS

It was naturally of great importance to determine how far the observed intensity of furnace lines might be affected by blends with lines belonging to foreign substances. The most disturbing elements, whose stronger lines appeared with those of iron in the furnace, were chromium, manganese, titanium, and vanadium, the two latter being given by the Acheson graphite. Fortunately, furnace spectra were available for these elements on the same scale as for iron, so that in the case of a suspected blend, it was a simple matter to see whether the furnace spectrum of the foreign substance gave that line of sufficient strength to appear when only a small quantity of the element was present as an impurity. When the furnace line of iron was probably affected in this way, the nature of the blend is given in the "Remarks" column of Table I. In the case of some blends it was not necessary to leave the intensity of the iron line wholly doubtful. For example, a low-temperature iron line is blended with the chromium line λ 5204.680, one of the strongest in that spectrum. The chromium line, however, is one of three which are affected similarly in any given source. From a furnace plate for chromium the strength of this line relative to the other two could be seen, so that on the iron plate it was possible to tell closely how much of the blend was due to the chromium line. The large scale of the second-order spectrum

was useful in separating lines frequently blended with lower dispersion, especially for iron lines occurring in the carbon flutings which are always troublesome at high temperature.

EXPLANATION OF THE TABLE

In Table I the wave-lengths in the first column are those of Rowland. The second column gives the intensities of these lines in the arc, estimated from spectra taken on the same plate with some of the best furnace spectra. The intensities were estimated on the same plan as for the furnace spectra. The large range of intensity, together with the low values for some lines, results from the choice of an arc spectrum not very strongly exposed, so that the contrasts are distinct and the weaker lines faint. A line graded as low as 2 is a moderately strong line in a fully exposed arc spectrum. All arc lines above a certain minimum strength are included in the table, whether they appear in the furnace or not, this minimum being determined by the fact that some lines as weak as this (usually of Class I A) do appear in the furnace spectrum. The arc lines listed are strong enough to be considered in any general treatment of the arc spectrum, and their action in the furnace is of interest.

The method of grading the furnace lines has been given. For both arc and furnace, the standard spectra to the violet of λ 4700 were obtained on a Seed "27" plate (old emulsion), and those for the remainder of the spectrum on plates or films bathed with the three-dye solution. The intensities between λ 4500 and λ 4700 and in the red region are low on an absolute scale by reason of decreased sensitiveness of the plates, but arc and furnace spectra are affected alike. The letter *n* in connection with the arc intensity denotes that the line belongs to the class of "nebulous" lines which show a large width in proportion to their density, while *r* and *R* indicate respectively that the line is partially or completely reversed. The approximate values of the three temperatures are given on p. 244.

TABLE I

TEMPERATURE CLASSIFICATION OF IRON LINES

λ (ROWLAND)	ARC	FURNACE			CLASS	REMARKS
		High Temp.	Medium Temp.	Low Temp.		
3884.518	3	1	..	..	IV	
3885.657	5	3	..	..	IV	
3886.434	40*R*	40*R*	40*R*	25	I B	
3887.196	15	15	15	10	I B	
3888.671	20	10	9	6	II	
3888.971	3	..	..	..	V	
3890.986	2	1	..	..	IV	
3892.069	3	..	..	..	V	
3893.542	7	3	..	..	IV	
3895.803	25*r*	20*r*	20	12	I B	
3898.032	8	1	..	..	V	
3898.151	10	8?	6?	4	I B?	Blend with *V* which disturbs at medium and high temperature. Probable intensity of *V* line subtracted
3899.171	2	1	..	..	IV	
3899.850	30*R*	30*R*	25	14	I B	
3900.681	2	..	..	..	V	
3903.090	20	12?	10?	6	II	Blend with moderately strong *Cr* line
3904.052	5	2	..	..	IV	
3906.628	8	15	15	9	I B	
3908.890	2	..	..	..	V	
3908.077	4	2	..	..	IV	
3909.976	3	..	..	..	V	
3913.775	4	3	..	..	IV	
3916.879	6	Tr.	..	..	V	
3917.324	8	10	10	4	I B	
3918.464	3	2	..	..	IV?	Not resolved on plates strong enough to give lines in furnace
3918.563	4					
3918.789	6	1	..	..	V	
3919.208	3	1	..	..	IV	
3920.410	20*r*	20*r*	20	15	I B	
3923.054	25*R*	30*R*	25	15	I B	
3925.790	4	1	..	..	IV	
3926.086	6	2	..	..	IV	
3928.075	30*R*	30*R*	25	15	I B	
3930.450	25*R*	35*R*	30	18	I B	
3932.785	4	1	..	..	IV	
3935.965	8	3?	..	..	IV?	Furnace line may be *Ba*
3937.479	3	1	..	..	IV	
3941.025	5	10?	9?	4?	I A?	May be partly *Sr* and *Co*
3942.586	6	1	..	..	V	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
3943.489	2	1	..	..	IV	
3945.033	3	Tr.	..	..	IV	
3945.260	4	Tr.	..	..	IV	
3947.142	4*n*	Tr.	..	..	IV	
3947.675	5	Tr.	..	..	V	
3948.246	6*n*	Tr.	..	..	V	
3948.925	10	..	..	..	V	
3950.102	10	8	4	Tr.	III	
3951.311	9	1	..	..	V	
3952.754	8	2	..	..	IV	
3953.303	4	Tr.	..	..	V	
3956.099	2	..	..	..	V	
3956.603	9	..	..	..	V	
3956.819	12	8	4	Tr.	III	
3957.177	4*n*	Tr.	..	..	IV?	Furnace line may be *Ca*
3963.252	6*n*	Tr.	..	..	V	
3964.663	3	..	..	..	V	
3966.212	10	10	8	2	II	
3966.778	10*n*	2	1	..	IV	
3967.570	8	1	..	..	V	
3968.114	4*n*	..	..	..	V	
3969.413	30	16	12	8	II	
3970.540	4	Tr.	..	..	IV	
3971.475	9	4	2	..	III	
3973.796	3	..	..	..	V	
3976.770	4	Tr.	..	..	IV?	Furnace line may be *Cr*
3977.891	12	9	4	1	II	
3981.917	7	12?	10?	2	I B	Close blend with *Ti* line which may predominate in furnace spectrum at medium and high temperature
3984.113	10	4	2	..	III	
3985.539	3	..	..	..	V	
3986.321	5	..	..	..	V	
3990.525	2	..	..	..	V	
3994.265	2	..	..	..	V	
3996.140	4	1	..	..	IV	
3997.115	2	..	..	..	V	
3997.547	15	7	2	..	III	
3998.205	10	4?	2?	..	III?	May be partly *Co*
4000.611	2	..	..	..	V	
4001.814	5	3	2	..	III	
4003.912	2	..	..	..	V	
4005.408	25	15	12	9	II	
4006.464	3	..	..	..	V	
4006.776	2	..	..	..	V	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4007.429	6	2	Tr.	..	III	
4009.864	10	9?	6?	1	II?	Furnace line chiefly *Ti*
4013.964	2	..	..	..	V	
4014.677	10	3	1	..	III	
4017.308	6	2	1	..	III	
4022.018	12	6	2	..	III	
4024.881	6*n*	..	..	..	V	
4029.796	3*n*	..	..	..	V	
4032.117	4	..	..	..	V	
4032.789	4	8	6	1	III?	Arc intensity low for Class III. Well separated from *Mn* 4033.224
4040.792	4	..	..	..	V	
4044.056	5*n*	..	..	..	V	
4044.766	6	2	..	..	IV	
4045.975	60*r*	30	22	15	II	
4055.023	3	..	..	..	V	
4055.189	3	..	..	..	V	
4057.499	2	..	..	..	V	
4058.372	4*n*	..	..	..	V	Blend with *Co*
4058.915	3	..	..	..	V	
4059.872	3	..	..	..	V	
4062.599	10	4	2	..	III	
4063.759	45	20	15	12	II	
4067.139	6	2	..	..	IV	May be partly *Cr*
4067.429	4	2	..	..	IV	
4068.137	8*n*	2	..	..	IV	May be partly *Mn*
4070.930	5*n*	1	..	..	IV	
4071.908	40	18	12	10	II	
4073.921	4*n*	1	..	..	IV	
4074.947	5	1	..	..	IV	
4076.792	8*n*	2	..	..	IV	
4078.515	4	2	..	..	IV	May be partly *Ti*
4079.996	4	1	..	..	IV	
4080.368	2*n*	Tr.	..	..	IV	
4084.647	6	1	..	..	V	
4085.161	4	1	..	..	IV	
4085.467	4	1	..	..	IV	
4096.129	4	2	1	..	III	
4098.335	4*n*	1	..	..	IV	
4100.901	3	10	8	3	I A	
4104.288	3	..	..	..	V	
4107.649	12	4	2	..	III	
4109.953	9	?	..	..	V	Weak if present at all in furnace. Close to strong *V* line at 4109.905
4113.117	3*n*	..	..	..	V	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4114.606	5	2	Tr.	..	IV	
4118.708	15	2	1	..	IV	
4120.368	5	2	..	..	IV	
4121.963	5	1	..	..	IV	
4122.673	4	1	..	..	IV	
4126.344	3*n*	..	..	..	V	
4127.767	7	2?	..	..	IV	Furnace line partly *Ti*
4127.957	3*n*	..	..	..	V	
4132.235	25	15	15	8	II	Furnace line very slightly affected by *V* blend
4133.062	8	3	..	..	IV	
4134.840	12	2?	..	..	IV	Furnace line partly *V*
4137.156	7	Tr.	..	..	V	
4140.089	2	6	4	2	I A	
4143.572	15	5	2	..	III	
4144.038	30	15	12	10	II	
4147.836	10	10	8	2	I B	
4149.533	5*n*	..	..	..	V	
4152.343	4	10	8	2	I A	
4154.071	10*n*	2	..	..	IV	
4154.667	12	4	2	..	III	
4154.976	9*n*	1	..	..	V	
4156.970	12	4	2	..	III	
4157.948	8*n*	1	..	..	V	
4158.959	5*n*	Tr.	..	..	V	
4171.068	5	1	..	..	V	
4172.296	5	1	..	..	V	
4172.923	4	9	9	3	I A	
4173.480	2	Tr.	..	..	IV	
4174.095	2	6	6	2	I A	
4175.082	5	10	10	5	I A	
4175.806	10	3	1	..	III	
4176.739	7*n*	2	..	..	IV	Blends with high-temperature line of *Mn*. Furnace line probably *Fe*
4177.698	4	10	10	4	I A	
4181.919	15	6	3	1	III	
4182.548	4	1	..	..	IV	
4185.058	10	3	1	..	III	
4187.204	20	10	7	2	II	
4187.943	20	10	7	2	II	
4191.595	15	9	6	1	III	
4195.492	5	1	..	..	V	
4196.372	4	1	..	..	IV	
4198.494	20	10	7	1	III	
4198.800	4*n*	Tr.	..	..	V	
4199.267	20	7	3	Tr.	III	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4200.148	1	9	8	4	I A	
4201.089	3*n*	..	..	..	V	
4202.198	30	18	12	9	II	
4204.101	10	3	1	..	III	
4206.862	3	12	12	8	I A	
4207.291	4	Tr.	..	..	V	
4208.766	3*n*	..	..	..	V	
4210.494	15	8	4	Tr.	III	
4213.812	5	2	..	..	IV	
4215.581	2	1	..	..	IV	
4216.351	8	10	12	8	I B	
4217.720	7*n*	1	..	..	V	May be partly *Cr*
4219.516	12	2	1	..	IV	
4220.509	4	1	..	..	IV	
4222.382	12	8	4	Tr.	III	
4224.337	6*n*	1	..	..	V	
4224.673	3*n*	..	..	..	V	
4225.619	6*n*	1	..	..	V	
4226.116	3	Tr.	..	..	V	
4226.584	3	Tr.	..	..	V	
4227.606	30	5	3	..	III	
4232.887	1	8	7	3	I A	
4233.772	18	9	6	1	III	
4236.112	25	10	8	2	II	
4238.188	4	Tr.	..	..	V	
4238.970	10*n*	2	1	..	IV	
4239.890	3	1	..	..	IV	
4240.014	2	3	2	..	I B?	Always faint. Would probably show at low temperature with long exposure
4245.422	6	3	2	1	II	
4246.251	3	..	..	..	V	
4247.591	12	3	2	..	III	
4248.384	4	Tr.	..	..	V	
4250.287	25	10	5	1	III	
4250.945	25	15	12	8	II	
4258.477	2	10	8	6	I A	Probably chiefly if not wholly due to *Fe*. A weak *Mn* line is given by Hasselberg at 4258.48 which appears faintly in *Mn* furnace but may be due to *Fe* which is present when *Mn* is used
4260.640	35	15	10	2	III	
4267.122	3	1	..	..	IV	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4267.985	5	1	..	..	V	
4268.915	2	Tr.	..	..	IV	
4271.325	20	10	5	2	III	
4271.934	35	20	15	12	II	
4282.565	12	10	7	3	I B	
4285.605	3	1	..	..	IV	
4291.630	4	10	10	8	I A	
4294.301	15	12	12	6	I B	
4299.410	18	9	5	2	II	
4305.614	3	Tr.	..	..	IV	
4308.081	35	20	15	10	II	
4309.541	4	1	..	..	IV	
4315.262	10	8	6	1	III	
4325.939	35	20	15	10	II	
4327.274	3	..	..	..	V	
4337.216	10	10	9	4	I B	
4351.711	3	..	..	..	V	
4352.908	9	8	8	2	I B	
4358.670	3	Tr.	..	..	IV	
4367.749	5	Tr.	..	..	V	
4368.071	2	4	3	1	I A	
4369.941	7	3	1	..	III	
4376.107	9	15	15	10	I B	Wider in proportion to density than 4415.293
4383.720	45r	30	20	12	II	
4388.057	3	Tr.	..	..	IV	
4388.571	4n	Tr.	..	..	IV	
4389.413	2	10	8	5	I A	
4391.123	4	Tr.	..	..	IV	
4404.927	30	20	15	9	II	
4407.871	5	3?	?	Tr.	III?	Allowance made for blend with *V*
4408.582	6	4	?	Tr.	III?	Blended with *V* except on one plate
4415.293	20	15	12	7	II	
4422.741	6	2	1	..	IV	
4427.482	10	12	12	9	I B	Wider in proportion to density than 4415.293
4430.785	6	4	2	1	II	
4433.390	3n	Tr.	..	..	IV	
4435.321	2	10	8	6	I A	Just resolved from *Ca*
4442.510	12	9	5	1	III	
4443.365	7	2	Tr.	..	IV	
4447.892	9	8	5	2	II	
4454.552	5	2	1	..	III	
4459.301	10	8	4	2	II	
4461.818	8	12	12	10	I B	
4466.727	12	12	10	6	I B	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4469.545	5*n*	1	..	..	IV	
4476.185	10	4	2	..	III	
4482.338	4	15	15	10	I B	Not fully resolved on most plates. 4482.338 seems about 4 times strength of 4482.438. In arc 4482.338 behaves as I A line and 4482.438 as I B
4482.438	6					
4484.392	4	..	..	..	V	
4489.911	3	12	12	8	I A	
4494.738	12	9	5	2	II	
4525.314	5*n*	1	..	..	IV?	Furnace line may be *V*
4528.798	18	12	9	3	II	
4531.327	8	10	7	4	I B	
4548.024	4	..	..	..	V	
4556.306	4*n*	..	..	..	V	
4592.840	5	8	6	2	I B	
4603.126	9	10?	9?	4?	I B?	Furnace line may be largely *Li*
4607.831	3*n*	..	..	..	V	
4611.469	5*n*	2	1	..	III	
4613.386	2*n*	..	..	..	V	
4619.468	3*n*	*	..	..	IV	
4625.227	3	*	..	..	IV	
4633.100	2	5	3	..	III?	Weak in arc for Class III
4637.685	3	*	..	..	IV	
4638.193	3	*	..	..	IV	
4647.617	6	*	1	..	IV	
4654.672	5	?	?	1	II?	Not fully resolved. 4654.672 blends with fluting line at high temperature
4654.800	5	..	..	..	V	
4667.626	6	..	..	..	V	
4668.243	6	*	..	..	IV	
4679.027	7	..	..	..	V	
4691.602	6	*	..	..	IV	
4707.457	8	*	..	..	IV	
4710.471	5	*	..	..	IV	
4727.582	3*n*	*	..	..	IV	
4728.732	3*n*	*	..	..	IV	
4733.779	4	*	4	1	I B?	
4736.963	12	*	*	2?	II?	Blend with head of *C* band and intensity doubtful
4741.718	3	..	..	..	V	

* Occurrence uncertain on account of strong carbon bands at high temperature, but *Fe* lines are weak in furnace, if present at all. Provisionally placed in Class IV.

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
4745.092	3*n*	..	..	..	V	
4768.595	3*n*	..	..	..	V	
4773.007	3	3	2	..	III	
4787.003	5	1	..	..	IV?	Furnace line may be *V*
4789.849	7	..	..	..	V	
4859.928	15	6	2	..	III	
4871.512	25	9	3	..	III	Furnace line may be slightly affected by *V* blend
4872.332	20	7	2	..	III	
4878.407	12	5	2	..	III	
4885.620	2	..	..	..	V	
4890.948	25	8	2	..	III	
4891.683	50	12	3	..	III	
4903.502	12	4	1	..	III	
4919.174	30	8	2	..	III	
4920.685	60	12	4	Tr.	III	
4924.956	3	..	..	..	V	
4938.997	10	3	..	..	IV	
4939.868	4	10	8	5	I B	
4946.568	4	5	..	..	IV	
4957.480	20	5	2	..	III	
4957.785	60	12	6	1	III	
4966.270	8	1	..	..	V	
4973.281	3	..	..	..	V	
4978.785	2	..	..	..	V	
4982.682	8*n*	..	..	..	V	
4983.433	5*n*	..	..	..	V	
4984.028	6*n*	..	..	..	V	
4985.432	7	Tr.	..	..	V	
4985.730	7	1	..	..	V	
4994.316	8	9	9	4	I B	
5002.044	12	1	..	..	V	
5005.896	10	..	..	..	V	
5006.306	20	4	1	..	III	
5012.252	12	10	9	8	I B	
5015.123	10	..	..	..	V	
5022.414	6	..	..	..	V	
5027.305	5*n*	..	..	..	V	
5028.308	4	..	..	..	V	
5041.255	7	7	6	3	I B	
5041.936	10	7	4	1	III	Blend with *Ca* probably has little effect on furnace intensity
5050.008	15	12	2	..	III	
5051.825	10	10	8	6	I B	
5065.207	6*n*	?	..	..	V	Concealed by *C* if present

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
5068.944	10	..	..	..	V	
5074.932	10*n*	..	..	..	V	
5079.409	6	3	Tr.	..	IV	
5079.921	4	6?	4	2	I B	Blend with *C* at high temperature
5083.518	7	10?	7	4	I B	Blend with *C* at high temperature
5098.885	8	4	Tr.	..	IV	
5107.619	6	4	3	2	I B	Blend on some plates makes estimates difficult
5107.823	8	3	2	1	II	
5110.574	10	8?	10	15	I B	Remarkably strong at low temperature. Blend with *C* at high temperature
5123.899	6	9?	5	3	I B	Blend with *C* at high temperature
5125.300	6*n*	..	..	..	V	
5127.533	5	8?	4	2	I B	Blend with *C* at high temperature
5133.870	20*n*	?	..	..	V	Blend with *C*. Very weak if present
5137.558	6*n*	..	..	..	V	
5139.427	10	4?	..	..	IV	Blend with *C* at high temperature
5139.644	20	4?	Tr.	..	IV	Blend with *C* at high temperature
5143.111	6	5	4	3	I B	
5151.020	6	5	4	2	I B	
5152.087	4	6?	3	1	I B	Blend with *C* at high temperature
5162.449	10*n*	?	..	..	IV?	Blend with *C* at high temperature. Probably present, but weak
5166.454	4	8	8	10	I A	Blend with weak *Cr* line which probably has little effect
5167.678	40	12	9	7	II	
5169.069	4	8	8	10	I A	
5171.778	20	10	6	3	II	
5191.629	20	4	..	..	IV	
5192.523	30	5	Tr.	..	IV	
5195.113	10	9	5	2	I B	
5198.888	4	2	..	..	IV	
5202.439	8	4	1	..	IV	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
5204.768	2	6?	6?	7?	I A	Blend with *Cr* 5204.680, the probable intensity of which is subtracted
5208.776	7	2	..	..	IV	
5215.353	6	2	..	..	IV	
5216.437	10	6	3	1	II	
5217.552	5	1	..	..	V	
5225.695	1	6	5	5	I A	
5227.043	15	2	..	..	IV	
5227.362	40	12	10	6	II	
5230.030	5*n*	1	..	..	V	
5233.122	40	7	2	Tr.	III	
5242.658	4	1	..	..	IV	
5247.229	1	5	6	5	I A	
5250.385	1	5	6	5	I A	
5250.817	6	3	Tr.	..	IV	
5255.121	1	8	8	6	I A	
5263.486	8	1	..	..	V	
5266.738	30	5	1	..	IV	
5269.723	60	25*R*	20	20	I B	
5270.558	30	12	10	5	II	
5273.558	4	1	..	..	IV	
5281.971	10	2	..	..	IV	
5283.802	18	3?	..	..	IV	Furnace line may be partly *Ti*
5302.480	10	1	..	..	V	
5307.541	2	3	1	..	III?	Difficult to classify. Arc intensity low for Class III
5324.373	30	6	1	..	IV	
5328.236	50	25*r*	20	20	I B	
5328.696	15	12	10	3	II	
5333.089	4	5	2	1	I B?	Strengthens rapidly for Class I B
5340.121	12	2	..	..	V	
5341.213	20	10	8	3	II	
5365.069	15*n*	Tr.	..	..	V	
5365.596	3	Tr.	..	..	V	
5367.669	20*n*	1	..	..	V	
5370.166	25*n*	1	..	..	V	
5371.734	50	25	20	20	I B	
5383.578	35*n*	2	..	..	V	
5393.375	10	3	Tr.	..	IV	
5397.344	40	20	18	18	I B	
5404.357	30*n*	2	..	..	V	
5405.989	40	20	18	18	I B	
5411.124	15*n*	Tr.	..	..	V	
5415.416	35*n*	2	..	..	V	
5424.290	45*n*	3	..	..	V	
5429.911	40	20	18	18	I B	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
5434.740	30	18	15	15	I B	
5445.259	15*n*	Tr.	..	..	V	
5447.130	40	20	18	18	I B	
5455.834	40	20	18	18	I B	
5463.494	10*n*	..	..	..	V	
5476.778	10	3	..	..	IV	
5497.735	15	15	12	5	I B	Compare with other I B lines to violet
5501.683	12	12	10	4	I B	
5507.000	18	18	15	6	I B	
5555.122	4	..	..	..	V	
5563.824	3	..	..	..	V	
5565.931	4	..	..	..	V	
5569.848	20	4?	..	..	IV	Blend with *C* at high temperature
5573.075	30	5?	..	..	IV	Blend with *C* at high temperature
5576.320	10	2?	..	..	IV	Blend with *C* at high temperature
5586.991	40	6	Tr.	..	IV	
5598.524	4	?	..	..	IV?	Blend with *C* at high temperature
5603.186	10	2?	..	..	IV	Blend with *C* at high temperature
5615.877	50	8	1	..	IV	
5624.769	10	3?	..	..	IV	Blend with *C* at high temperature. May be affected by *V* blend
5638.488	3	..	..	..	V	
5655.715	4	..	..	..	V	
5659.052	10	3	..	..	IV	
5662.744	6	1	..	..	V	
5701.772	7	5	..	..	III?	Would be expected to show at moderate temperature on strong plates
5709.601	10	3	..	..	IV	
5753.344	5	..	..	..	V	
5763.218	10	Tr.	..	..	V	
5859.809	5	..	..	..	V	
5862.582	8	..	..	..	V	
5884.028	4	..	..	..	V	
5905.895	3*n*	..	..	..	V	
5914.335	8	..	..	..	V	
5930.406	8	..	..	..	V	
5934.881	5	..	..	..	V	
5952.943	3	..	..	..	V	
5975.575	4	..	..	..	V	
5977.007	5	..	..	..	V	
5983.908	6	..	..	..	V	
5985.040	8	2	..	..	IV	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
5987.290	6	..	..	..	V	
6003.239	8	..	..	..	V	
6008.785	9	..	..	..	V	
6020.401	10*n*	..	..	..	V	
6024.281	15	..	..	..	V	
6027.274	4	..	..	..	V	
6042.315	2	..	..	..	V	
6056.227	4	..	..	..	V	
6065.709	15	7	4	..	III	
6078.710	4*n*	..	..	..	V	
6102.392	5	..	..	..	V	
6103.400	3	..	..	..	V	
6136.829	20	10	6	..	III	
6137.915	18	7	3	..	III	
6141.938	4	..	..	..	V	
6157.945	4	..	..	..	V	
6170.730	4*n*	..	..	..	V	
6173.553	3	3?	1	..	III	Blend with *C* at high temperature
6191.779	20	10	7	1	II	Weak at low temperature for Class II
6200.527	4	1	..	..	IV	
6213.644	5	4	2	..	III	
6219.494	6	5	2	..	III	
6230.943	25	12	8	..	III	Blend with *V* which probably has little effect
6232.856	5	..	..	..	V	
6246.535	15	1	..	..	V	
6252.773	20	9	5	..	III	
6254.450	6	4	2	..	III	
6256.572	4	2	1	..	III	
6265.348	6	5	3	..	III	
6280.833	2	9	7	3	I A	
6291.184	3*n*	..	..	..	V	
6298.007	5	4	2	..	III	
6301.718	15	2	Tr.	..	IV	
6302.709	6	..	..	..	V	
6318.239	10	7	3	..	III	
6322.907	5	2	1	..	III	
6335.554	10	8	4	..	III	
6337.048	12	1	..	..	V	
6344.371	2	1	Tr.	..	III	
6355.246	4	2	1	..	III	
6358.898	3	9	7	3	I A	
6380.958	3	..	..	..	V	
6393.820	15	12	8	Tr.	III	
6400.217	25	4	2	..	III	
6408.233	8	..	..	..	V	
6411.865	12	2	1	..	IV	
6420.169	5*n*	..	..	..	V	

TABLE I—*Continued*

λ (Rowland)	Arc	Furnace			Class	Remarks
		High Temp.	Medium Temp.	Low Temp.		
6421.570	10	8	5	..	III	
6431.066	10	10	7	Tr.	III	
6462.965	5	?	?	?	?	Occurrence in furnace uncertain on account of blend with low temperature *Ca* line
6469.408	2	..	..	..	V	
6475.846	3	1	..	..	IV	
6482.098	4	1	..	..	IV	
6495.213	25	15	10	2	II	
6546.479	10	7	3	..	III	
6569.460	5	..	..	..	V	
6575.270	2	..	..	..	V	
6593.161	10	6	2	..	III	
6594.121	4	3	..	..	IV	
6609.360	4	2	..	..	IV	
6633.995	7*n*	..	..	..	V	
6663.701	8	4	..	..	IV	
6678.235	12	9	3	..	III	
6750.407	6	3	..	..	IV	
6828.850	4	..	..	..	V	
6841.598	4	..	..	..	V	
6843.913	4	..	..	..	V	
6855.419	5	..	..	..	V	
6945.477	4	2	..	..	IV	
6979.120	3	1	..	..	IV	
7187.645	5	..	..	..	V	These lines are really stronger than indicated, as plate loses sensitiveness rapidly in this region
7207.715	3	..	..	..	V	

DISCUSSION OF THE CLASSIFICATION

An examination of Table I shows a considerable variety as to the rate of growth among lines placed in the same class; but there is little to be gained by increasing the number of classes to cover these variations. There appears in all classes to be a continuous change in the intensities of furnace lines with temperature, the several classes being distinguished by the rate of change shown by each. As the scale has been arranged in Table I, the low-temperature lines of Classes I A and I B strengthen slowly or remain nearly the same for the three temperatures. As a rule,

there is little difference between medium and high temperature for these lines. If the intensities of Class II lines had been graded so as to show approximate equality for the three temperatures, the lines of Classes I A and I B would have shown a gradual weakening as the temperature rises. This point of view, however, does not seem to me to represent the true state of affairs as well as that adopted in the arrangement of Table I, which shows the Class II lines rapidly increasing in strength while the lines of Classes I A and I B about hold their own. Class II and Class III lines usually show a regular change of intensity with temperature, but many variations occur in the rate of change for individual lines.

If we regard the arc conditions as equivalent to a higher-temperature stage than that of the furnace, it is necessary to assume that large changes may occur in the temperature interval separating the two sources, and of very different magnitudes for different lines. However, lines in the same class, when near together in the spectrum so that the intensities were estimated from the same set of plates, show a fair degree of correspondence between the rate of change in the furnace and that for the interval between furnace and arc. This is best seen for lines in Classes II and III. So that, making allowance for difficulties in forming a concordant scale of intensities for arc and furnace lines, it may be said that if each class maintains the rate of change which it shows through the temperature range of the furnace observations (about 800°), it would be expected to reach an arc intensity of the order of that observed.

To account for the behavior of Class I A lines on the basis of a continuous change with temperature, we must adopt a scale of gradation such that these lines will diminish in intensity through the furnace range if they are to reach the weakness shown in the arc, where many of them, such as $\lambda\lambda$ 4258.477, 5225.695, and 5255.121, can only be given an intensity comparable with the furnace line by exposures of the arc so long as to give very high intensities to the lines of other classes. As compared with the rest of the spectrum, the arc is certainly at a great disadvantage in producing these lines. It is an interesting question whether the

furnace would show them relatively as weak if it could be brought to the temperature of the arc. Judging from the way the lines of Class I A maintain their strength through the range of furnace temperatures which has been produced, this seems unlikely. With two or three exceptions, the lines of Class I A have not been considered in investigations on the variation of arc and spark lines, doubtless because of their faintness in these sources. Their appearance in the flame and core of the arc is important and will be described later in this paper.

The high furnace temperature required to give the red end of the spectrum is noteworthy. The low intensity of the red lines is due in part to the decreased sensitiveness of the plates for this region, but very long exposures with both the large and small spectrographs have failed to give any red lines of iron at low temperature, except traces of the strongest arc lines and the two lines $\lambda\lambda$ 6280.833 and 6358.898 belonging to Class I A. At medium and high temperatures a large number of red lines were obtained. This behavior has placed almost all of these lines in classes not lower than III. The relative ease with which the blue end of the spectrum appears shows that the emission of the line spectrum does not follow closely the laws for an incandescent solid. This was well shown in a two-hour exposure with the very bright 1-meter concave grating, a bathed film being used. The furnace temperature measured about 1800° C. The exposure was so long that the weak continuous spectrum given by the vapor (probably largely through light from the wall of the tube reflected by the vapor particles) was able to impress itself on the plate distinctly in the red and orange. Iron lines were almost entirely lacking for this region, while they were plentiful in the blue where the continuous spectrum was very weak. This behavior, however, does not present an exception to any known law of spectral distribution, since no series have been recognized among iron lines, and a resemblance to the intensity gradations for an incandescent solid can be expected only for lines thus related.

Other notable groups of strong arc lines which are given only at the higher furnace temperatures occur at λ 4860 to λ 4960 and λ 5570 to λ 5625. The "nebulous" lines, indicated by *n* in con-

nection with the arc intensity, are among the most difficult to obtain in the furnace. Some of the best examples occur between λ 5360 and λ 5460. By long exposure at high temperature it was possible to obtain all of these distinctly, so that probably similar lines throughout the spectrum can be obtained under the same conditions. They usually belong clearly in Class V.

LINES WHICH MAY BE USED AS CRITERIA OF TEMPERATURE CONDITIONS

In sources for which a difference in temperature is considered to have a large part in the observed variations in the spectrum, a comparison of the intensities of lines near together which show a very different behavior in the furnace will usually show, in a general way at least, how the temperatures of the sources are related. Many pairs and groups of lines in Table I may be used in this way, but the following (Table II, p. 268) are suggested as especially suitable. The two lines in each case show a decided difference, both as to the temperature at which they appear and the rate of their change.

Some of the pairs in Table II are especially useful in deciding whether a given source more nearly resembles the arc or the furnace. Cases in which a Class I A line is paired with a line of Class II or Class III are favorable for this purpose. The behavior of the three lines $\lambda\lambda$ 5498, 5502, 5507 as compared with the strong I B lines from λ 5456 to λ 5269 is peculiar. These three lines are weak at low temperature but increase rapidly in the interval covered by the three furnace temperatures. The other I B lines in this region are strong at low temperature and increase slowly, but show a much greater increase in the interval between furnace and arc than is shown by the group of three, which would seem to belong in a class between Classes I B and II. If it were not for their relatively low intensity in the arc, the three lines would belong clearly in Class II. λ 5333.089 shows a very similar behavior in furnace and arc.

PRELIMINARY ACCOUNT OF THE ULTRA-VIOLET FURNACE SPECTRUM

A set of furnace photographs of the ultra-violet for which the iron arc spectrum reaches as far as λ 2300 has been made with the

1-meter concave grating already described. In most respects these are very satisfactory, but as a concave grating spectrograph of 15 ft. radius is under construction, it will be desirable to supplement

TABLE II

NEIGHBORING LINES WHICH ARE DIFFERENTLY AFFECTED IN THE FURNACE

Å	Class	Å	Class
3950.102	III	4459.301	II
3951.311	V	4461.818	I B
3966.212	II	4489.911	I A
3966.778	IV	4494.738	II
4100.901	I A	4528.798	II
4107.649	III	4531.327	I B
4177.698	I A	4919.174	III
4181.919	III	4939.868	I B
4199.267	III	5050.008	III
4202.198	II	5051.825	I B
4206.862	I A	5166.454	I A
4210.494	III	5171.778	II
4216.351	I B	5225.695	I A
4219.516	IV	5233.122	III
4232.887	I A	5341.213	II
4233.772	III	5371.734	I B
4250.287	III	6246.535	V
4250.945	II	6252.773	III
4271.325	III	6280.833	I A
4271.934	II	6301.718	IV
4260.640	III	6335.554	III
4308.081	II	6337.048	V
4291.630	I A	6355.246	III
4294.301	I B	6358.898	I A
4415.293	II	6393.820	III
4427.482	I B	6411.865	IV

them by large-scale photographs covering at least the portion where lines are most numerous in order to reduce the uncertainties as to blends and show more clearly the character of the lines. As the small spectrograph is adjusted, the second order can be followed from λ 4000 to about λ 2800, from which point the greater strength

of the first order is an advantage for the very short wave-lengths. The scale in the second order being 8.5 Å. per mm and the definition very sharp, the spectrum can be examined to good advantage under the microscope of a measuring machine with fairly high power. The resolving power of the grating is sufficient to separate sharp lines at λ 2800 which are 0.15 Å. apart. While postponing the detailed publication of the ultra-violet spectrum, a few of the leading features may be given here.

At high temperature, the line of shortest wave-length thus far photographed has been λ 2463. At medium temperature, prolonged exposures have yielded lines beginning at λ 2706; while the lower furnace temperature has thus far failed to show any lines of wave-length less than λ 3440. These limits are interesting as showing the gradual extension into the ultra-violet with increasing temperature. As absolute limits for a given temperature, they would probably be modified somewhat by a quartz prism apparatus or by a grating reflecting the short waves more strongly. Photographic emulsions more sensitive to this region would also give an extension if the furnace vapor does not absolutely cease to radiate at the limits observed. At the highest temperatures I have suspected that absorption by the vapor in the furnace tube may act in shortening the ultra-violet spectrum. The generation of vapors of all kinds, including those from carbon and the tube impurities is then very vigorous and the extension toward shorter wave-lengths has varied for different runs of the furnace made at approximately the same high temperature. For medium and low temperatures the results in this regard have been more consistent. This feature makes more difficult the comparison of temperatures between the furnace and any other source, based on the extension into the ultra-violet.

The classification adopted in Table I would have a different meaning if applied to the extreme ultra-violet, since there is an actual discontinuance the spectrum of at certain points according to the temperature employed. Thus the lines below λ 2700 would go into Classes IV and V, with a large addition of Class V lines which are given only in the arc for this region. From λ 2700 to λ 3440 numerous Class III lines would enter the list, while from

λ 3440 into and through the visible region all of the classes would appear.

It was found when a graphite plug was placed in the middle of the furnace tube and the furnace heated to different temperatures that the extension of the continuous spectrum into the ultra-violet for each temperature varied in a way closely corresponding to that of the line spectrum; but when such continuous spectra were taken on the same film at low, medium, and high temperatures each of them reached at least 300 Å. farther than it has been possible to obtain lines at the same temperature, even with much longer exposures than were used for the continuous spectra. The furnace tube with a plug at its center obviously approximates black-body conditions, and the inference is that the radiation of a black body is stronger than the emission of a line spectrum at the same temperature. Some experiments in which the furnace was charged with metallic calcium containing as impurities several other elements of low melting-points showed the same relation. As far as experiments have proceeded, the furnace never gives a bright line as far to the violet as the continuous spectrum from a plugged tube will easily extend at the same temperature.

A COMPARISON OF THE INTENSITY VARIATION SHOWN BY THE CORE AND THE FLAME OF THE IRON ARC

In the earlier work done at this observatory on the spectra of sun-spots,[1] the relative intensities of lines given by the core and by the outer envelope of the arc were compared and ascribed in the main to temperature differences. Some experiments at that time with a furnace of Moissan type in which a carbon tube containing iron was heated by an arc playing over its outer wall gave spectra resembling that of the outer arc vapors. The material obtained in the present work for a variety of furnace temperatures offered a means of testing the validity of the hypothesis as to the relative temperatures of arc vapors. A series of large-scale photographs was made with the image of the arc focused so as to give its cross-section on a long slit. The arc could be made to burn

[1] Hale, Adams, and Gale, *Contributions from the Mount Wilson Solar Observatory*, No. 11; *Astrophysical Journal*, **24**, 185, 1906.

very steadily, the greenish core showing at the middle of the slit, while the flame vapors, gradually decreasing in luminosity, spread toward the end. The spectrum photographed records the intensity of each line as given by the vapor in a horizontal plane through the arc, about midway between the poles. The arc lines then show the following characteristics:

1. The line is always most intense at its middle, where the radiation is given by two thicknesses of flame vapor, together with that of the core. From this point the line narrows, but at a rate which differs for different lines. The "short and long line" classification of Lockyer is based on this characteristic.

2. The ability of the cooler vapors of the flame to give a certain line is registered by the strength of the extensions from the center. This varies greatly for different lines and in general the distance from the center to which a line extends and the rate at which it strengthens from the end toward the center resemble, respectively, the stage of temperature at which a line appears in the electric furnace and the rapidity of its increase in strength with temperature.

This relation is shown in Fig. 1, the lower part of which represents by the shaded rectangles the relative strengths of the several classes at low, medium, and high temperature, while the upper portion gives sketches of typical lines of each class showing one-half of the line when the cross-section of the arc is projected on the slit in the manner described. The broken horizontal lines in the upper portion inclose parts of the spectrum line which may be considered as appearing in the core (reinforced by the superposed flame in the line of sight) and in the inner and outer portions of the flame vapors respectively. Photographs which give lines similar to those in this figure have been made by placing fine wires across the slit at the proper intervals.

Taking the several classes in turn, the I A lines are always weak in the arc, but they run some distance into the flame without much diminution of intensity. Judging from their appearance, very little of their strength is given by the central core of the arc. They do not, however, appear in the outermost vapors of the flame, as do the lines of Classes I B and II, the arc differing materially from the furnace in this respect. The furnace sometimes

shows a I A line very similar at all temperatures to a neighboring I B line, while the latter is far stronger in the arc. Examples are $\lambda\lambda$ 4291.630 and 4294.301, also $\lambda\lambda$ 4489.911 and 4466.727.

Lines of Class I B and the stronger ones of Class II run farthest into the flame vapors but show a decided contrast in the way in

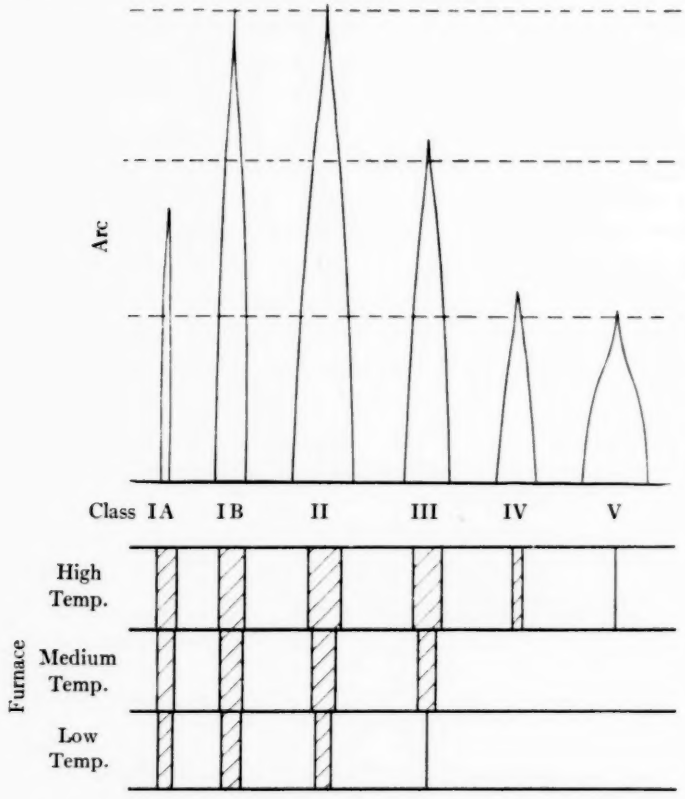

FIG. 1.—Comparison of relative intensities of furnace lines with the intensities of lines produced by different parts of the arc.

which they thicken as they approach the core. Adjacent lines of Classes I B and II may extend the same distance into the flame, but the Class II lines will often be two or three times as strong as the other at the core. $\lambda\lambda$ 4415.293 and 4427.482 are good examples and there are many similar ones. This behavior in the arc

corresponds closely with that in the furnace, both being low-temperature lines as regards initial appearance, but the I B lines being *relatively* strong at low temperature.

Class III lines do not extend as far into the flame as those of Classes I B and II, but strengthen more rapidly toward the core. This condition becomes more pronounced for Classes IV and V, strong lines of the latter being very wide in the core and showing little extension into the flame. Good examples are $\lambda\lambda$ 5383.578, 5415.416, and others in that region.

Taken as a whole, it is found that an iron-arc spectrum produced by a plane grating in this way shows that the lines divide into classes according to their rate of growth in intensity as we pass from flame to core, in much the same way as they have been classified as to their rate of strengthening at various furnace temperatures. This agreement is only qualitative. There are many differences in detail for lines other than those of Class I A, and only the furnace is available if the spectrum resulting from a measured temperature is desired. However, the furnace results indicate that the changes in relative intensity of lines observed in passing from the outer vapors to the core of the arc are due largely to temperature differences.

If the melting- and boiling-points of iron are taken as 1500° C. and 2450° C. respectively, it is evident from the furnace results that iron vapor can be made to radiate much below the boiling-point. Since the highest furnace temperature is above the boiling-point of iron, the arc should give a spectrum similar to that of the furnace if the metal were simply boiling in the arc. We find, however, that to produce the arc spectrum would require the equivalent of a much higher temperature than is given by the furnace. Experimental evidence is lacking as to the exact nature of this difference between furnace and arc conditions, but it would seem that it is to be attributed mainly to the high electronic speeds given by the arc discharge.

Another point of interest is the fact that there appears to be little reason to ascribe the high intensity of Class I B and Class II lines in the flame of the arc to chemical action, especially to the increased oxidation to be expected in the flame vapors. In the

furnace such chemical action as there is may be expected to increase with the temperature, and it is the low-temperature spectrum, presumably with minimum chemical action, which resembles most closely that given by the outer vapors of the arc. In fact, the material at hand indicates that relative changes in the spectrum do not result in any large degree from increase of oxidation. In the recent investigation of pressure effects[1] a set of furnace photographs was made for the blue and green-yellow regions of iron at atmospheric pressure and in compressed air up to 24 atmospheres. The brightness of the lines greatly increased, the radiation becoming stronger from end to end of the tube, as was evidenced by the general widening and the larger number of reversals; but no selective action, such as the bringing-out of some lines and the suppression of others, was to be seen, the nearest approach to the latter effect being for some high-temperature lines which did not reverse but were rendered very broad and hazy by pressure, so that unless the plates were strongly exposed such lines appeared greatly weakened. At atmospheric pressure, the spectrum is so closely similar to that in a partial vacuum, as regards relative intensity of lines, that the probability of oxidation playing an important part in the modification of a line spectrum, aside from general increase of intensity, seems very small.

COMPARISON WITH THE SPARK SPECTRUM

The evidence offered by the furnace is in agreement with the general phenomena of the arc and spark to the effect that the lines which are stronger in the spark than in the arc require a very high temperature or other abnormally violent excitation to bring them out. With one exception, all of the enhanced lines of iron listed by Lockyer[2] are entirely lacking in the furnace spectra. Only λ 3935.965 appears at high temperature, and this may be a barium line agreeing closely in wave-length which would be expected to show in the furnace. Most of the enhanced lines of iron are very faint in the arc, but the condition as to the weakness or absence of

[1] *Contributions from the Mount Wilson Solar Observatory*, No. 60; *Astrophysical Journal*, **35**, 183, 1912.

[2] "Tables of Wave-Lengths of Enhanced Lines," Solar Physics Committee, 1906.

such lines in the furnace spectrum holds for other elements such as titanium, many of whose enhanced lines are strong in the arc.

A comparison with iron spark spectra made in this laboratory shows that the lines of Class I A, while present in the condensed spark, are produced with somewhat greater difficulty than in the arc, as would be expected from the general relations of arc and spark spectra. The connection of temperature changes in line intensities with those resulting from the use of self-induction with the spark will be made the subject of a later study.

COMPARISON WITH THE FLAME SPECTRUM

The investigations of Hemsalech and de Watteville have furnished material sufficient to establish the general character of flame spectra in reference to that of the furnace, though complete lists of lines for some of the flames have not been published. The flame lines given by de Watteville[1] as occurring in the outer vapors and those appearing at the boundary of the cone of a special air-coalgas flame correspond closely to the furnace spectra at low and medium temperatures respectively. The flame spectrum obtained by de Watteville extends farther into the ultra-violet than I have been able to photograph with the furnace, but his use of a quartz prism spectrograph for the flame may largely account for this, as comparisons of the extension into the ultra-violet are valid only when the same optical system is used. The possible absorption of short waves by the furnace vapors previously referred to may also affect this comparison with the flame. The list of flame lines does not include those which I have placed in Class I A for the furnace, with the exception of λ 4489.911. This would be remarkable were it not that de Watteville clearly omitted lines of this character which were relatively weak in the self-induction spark used by him for identification of the iron lines.

In an improved form of apparatus in which the iron vapor was generated by an arc in a closed chamber and then mixed with the gas which passed to the flame, Hemsalech and de Watteville[2]

[1] *Philosophical Transactions*, **204** A, 139, 1904.

[2] *Comptes rendus*, **146**, 859, 1908.

observed that an air-coalgas flame gave next to the cone a supplementary spectrum which did not appear in the hotter flames produced by combinations of oxygen with coalgas, air with hydrogen, and oxygen with hydrogen when used in the same apparatus. In a later paper[1] they noted that this "supplementary spectrum" contained a large number of lines in the ultra-violet which are given most strongly near the poles of the iron arc, many of them being relatively stronger in the spark than in the arc. These lines extend from λ 2374 to λ 3936.

Some of these "polar" lines appear in the high temperature furnace, but most of them are below λ 2700, in which region the furnace gives only the stronger arc lines. Recently the source named by the writer the "tube-arc" has been operated. The furnace tube is allowed to burn through with a high vaporization of carbon and the arc thus formed around the periphery has been shown[2] in the case of titanium, to give the enhanced lines strongly predominating. The tube-arc spectrum of iron reaches a shorter wave-length than the furnace spectrum, lines as far as λ 2327 having been photographed. Most of the polar lines noted by Hemsalech and de Watteville in the flame spectrum occur in the tube-arc, but I have not as yet been able to identify with certainty any of the enhanced lines of iron in the visible region. It thus appears that the polar lines in the ultra-violet do not require as strong excitation as do the enhanced lines of the visible spectrum, which is borne out by the fact that the former class of lines appear through the central region of the arc, though strongest close to the poles.

As to why the supplementary spectrum containing the polar lines did not appear in the hotter flames, I would venture to suggest that the condition noted by Hemsalech and de Watteville in a later paper[3] may furnish the explanation, namely, that in the more intense flames the strong current of gas carries the particles of iron vapor through the region of highest temperature too rapidly for the temperature to exert its full effect, while the more quiet

[1] *Comptes rendus*, **146**, 1389, 1908.

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 65; *Astrophysical Journal*, **37**, 119, 1913.

[3] *Comptes rendus*, **150**, 329, 1910.

conditions of the Bunsen flame may permit such temperature as exists to be fully felt. In other words, iron vapor introduced into the oxyhydrogen flame by this method may not be heated to the same degree as a solid body would be on which the flame is allowed to play.

The oxyhydrogen flame spectrum of iron, of which 118 lines from λ 2483 to λ 5372 are given by Hemsalech and de Watteville,[1] must be classed as a low-temperature spectrum. Without exception, the lines in the visible portion belong in Class I B or Class II, whose strength at low temperature is characteristic. Many other lines should have appeared if the effective temperature of this flame had been as high as that for the medium-temperature furnace spectrum of Table I.

A study by the same authors[2] of the iron spectrum given by the oxyacetylene flame showed that in addition to the lines of the oxyhydrogen flame a set of lines occurs which are characteristic of the cone of the Bunsen flame, though not so strong as in the latter. The furnace spectrum shows that nearly all of these lines are in either Class III or Class II. If in the latter class, they show a rapid increase from low to medium furnace temperature. The strong Class III lines near λ 4900 are given in this set. This serves to place the oxyacetylene flame as corresponding to the furnace at the lower limit of the medium temperature. A conclusion equivalent to this was reached by Hemsalech and de Watteville by a comparison with the furnace results then at their disposal.

The several flames may thus be placed in the following order of their effective temperatures in producing radiation from iron vapor, the temperatures given being those read for the furnace when it gives in the visible region a spectrum similar in the lines present and in general relative intensities to that of the corresponding flame spectrum.

Flame	Furnace Temperature
Air-coalgas (outer vapors)	Below 1800° C.
Oxyhydrogen	About 1800°
Oxygen-coalgas Oxyacetylene	About 2000° to 2100°
Air-coalgas (cone)	About 2200°

[1] *Ibid.*, **146**, 962, 1908.

[2] *Ibid.*, **150**, 329, 1910.

Judging from the furnace spectra, the flame temperature need not be higher than 2200° to produce the spectrum shown by the cone of the Bunsen flame and it may be appreciably lower. Furnace temperatures of 2400° and over not only gave a spectrum much richer in lines than is given by the Bunsen cone, but those lines which show a rapid growth with temperature are relatively much stronger. The lines classed as I A in the furnace spectra would be of value as an index to these low temperatures, but they were omitted by Hemsalech and de Watteville.

The difficulty remains to reconcile the above gradation of flames in the order of their spectroscopic efficiency with their relative temperatures as measured by melting-point tests. It seems at least plausible, however, that the explanation involves the mechanics of the flame gases, rather than the real thermal condition of each flame.

There is not enough material at hand to test definitely whether a certain flame yields the same spectrum as that of the furnace at equal temperature, though in the visible spectrum at least the evidence points that way. The list of flame lines by de Watteville[1] contains no lines between λ 3900 and λ 5600 which do not occur in the furnace. The medium-temperature furnace spectrum (2100°–2300°) contains more lines than the flame, the high-temperature furnace shows many more. Practically the same condition exists to about λ 2700; while farther in the ultra-violet, each source shows a number of lines apparently not given by the other. A further investigation of the extreme ultra-violet is required to show whether the use of different spectrographs and possibly the presence of foreign substances in furnace or flame (the identification of lines in this region often being uncertain) may be responsible in any large degree for this difference.

THE QUESTION OF TEMPERATURE RADIATION

The later work with the furnace has given no ground to modify the view expressed by the writer at the close of a paper[2] published

[1] *Op. cit.*

[2] *Contributions from the Mount Wilson Solar Observatory*, No. 35; *Astrophysical Journal*, **29**, 190, 1909.

over three years ago, in which it was pointed out that the furnace is not suited for crucial experiments as to the mechanism of the radiation, but that temperature is obviously the agent which sets this mechanism in operation and controls the observed variations in the furnace spectrum.

The view appears to be gaining ground among spectroscopists that the emission of a line spectrum by temperature alone is possible and that quite probably it is given by the tube furnace, though definite proof of this cannot be claimed to have been offered. Opinions along this line have been clearly expressed in recent writings by Kayser[1] and by Schuster.[2] The vital question is whether a part of the translatory energy of the molecules due to heat can be changed to the "internal energy" which gives the emission of light. In this paper I wish to draw attention to several characteristics of furnace phenomena which bear more or less directly on the general problem.

1. There is unquestionably strong ionization from the carbon tube at the temperatures employed. Recent experiments by Harker have shown this to be the case at atmospheric pressure, while its existence at low pressure is well known.

2. Chemical reactions take place which are probably mainly of two kinds—combination with oxygen, the total exclusion of which is all but impossible even with the vacuum furnace, and the formation of iron carbide. The residue of iron is always found sticking fast to the interior of the tube and appears to eat into the graphite, this being perhaps in part due to the porosity of the latter.

3. The furnace radiation does not depend upon the existence of a potential difference. When the current is broken, the high-temperature lines gradually disappear, while some of the low-temperature iron lines have been observed 5 minutes, and the D lines of sodium 16 minutes after breaking the current. There is every reason to believe that if the tube could be as efficiently heated by a flame or other non-electrical source of heat, the radiation from the inclosed vapors would be the same as observed in these experiments.

[1] *Zeitschrift für wissenschaftliche Photographie*, **8**, 151, 1910.

[2] Article "Spectroscopy," *Encyclopaedia Britannica*, 11th ed.

4. The increased oxidation due to the presence of air at, or much above, atmospheric pressure appears to have no distinct effect upon the spectrum for a given temperature aside from a general widening of the lines.

5. Many experiments have shown that when the furnace tube is obstructed by a plug or other mass of solid matter so as to approach black-body conditions, the weaker lines are entirely concealed by the continuous spectrum and the stronger lines thrown into absorption, indicating that the black-body radiation is stronger than that of the metallic vapor for any given wave-length.

SUMMARY

The ground covered in this investigation may be summarized as follows:

1. The relative intensities of iron lines in the visible spectrum have been given for three furnace temperatures and for the arc, with a division into six classes based on the temperature at which a line appears in the furnace and its rate of growth with increase of temperature.

2. The changes in relative intensities of lines observed in passing from the furnace to the arc may in general be accounted for by a difference in conditions equivalent to a large temperature difference, though one class of furnace lines presents difficulties in establishing a clear relation of this kind.

3. The red end of the iron spectrum appears to require high temperature for its production as compared to the blue region, and the distribution of lines through the visible spectrum bears little resemblance to the intensity gradation observed for the spectrum of an incandescent solid.

4. A preliminary examination of the ultra-violet showed this region to be very rich in lines given by the furnace. The extension of the line spectrum toward shorter wave-length with increase of temperature was observed, it being found that lower limits were reached for a given temperature by the spectrum of an incandescent solid.

5. A list is given of pairs of lines whose members belong in different classes as regard response to temperature changes and

may be used in estimating the relative temperatures of light sources.

6. The increase in intensity of lines from the outer vapors into the core of an iron arc was found usually to resemble the rate of growth shown by the same lines with rising furnace temperature. This renders it unlikely that chemical reactions in the outer vapors affect the relative intensity of arc lines in any large degree.

7. The enhanced lines of iron in the visible region have not been observed in the furnace spectrum.

8. A comparison with published data on flame spectra has shown how the various flames are probably related as to effective temperatures in producing radiation. Except perhaps in the ultra-violet, furnace spectra at low and medium temperatures are found to be very similar to those of the several flames.

9. While presenting no definite proof that temperature radiation in a strict sense takes place, the position of temperature as the exciting and regulating agent in furnace phenomena seems to be clear.

Miss Sheldon of the Computing Division has rendered frequent assistance in this work, especially in the examination of plates for the ultra-violet spectrum.

MOUNT WILSON SOLAR OBSERVATORY
October 17, 1912

ON THE MEASUREMENT OF THE ZEEMAN EFFECT

By G. F. C. SEARLE

In the *Astrophysical Journal* for November 1911 (**34**, 312) J. E. Purvis drew attention to the discrepancies between the values of the Zeeman effect obtained by him in the case of certain lines in the spectrum of chromium and the values obtained by Miller, by Hartmann, and by Babcock. On reducing to a common value of 23,850 gausses the magnetic forces which the four observers stated they had employed, Purvis found the following results for the separation of the triplet arising from the line λ 4646.39:

VALUES OF $\frac{d\lambda}{\lambda^2} \cdot 10^8$ FOR 23,850 GAUSSES

Purvis	Miller	Hartmann	Babcock
+0.92	+1.31	+1.21	+1.42
0	0	0	0
−0.92	−1.31	−1.21	−1.42

Similar results were found for other triplets.

Purvis says of his own work: "The field-strength I used was 39,980 C.G.S. units, and there can be no doubt of its accuracy."

In the *Astrophysical Journal* for April 1912 (**35**, 213) A. Cotton discusses the discrepancies to which Purvis had called attention and concludes that the magnetic field in the gap of his magnet, which Purvis assumed to be 39,980 gausses for an exciting current of 20 amperes, was not, in fact, so great. From a comparison of Purvis' results for the Zeeman effect with those of other observers, Cotton deduces that the field used by Purvis was approximately 30,000 gausses, instead of 39,980 gausses.

The value of 39,980 gausses assigned by Purvis for the magnetic field due to a current of 20 amperes in the coils of his magnet, when the trunkated conical pole-pieces are terminated by disks 7 mm in diameter and the gap is 4 mm wide, is taken from the results of a series of measurements made by myself, with assistance,

in 1903. The magnet was supplied by W. G. Pye & Co. of Cambridge, England, and my tests were made within a few days after its delivery by the makers. The results of some of those tests are shown in Fig. 1 by the curve marked (2) and numerical values are given in Table I. The curve marked (1) represents results obtained in 1903 with pole-pieces 0.3 cm in diameter and a gap of 0.15 cm. The testing coil used for curve (2) had a larger diameter than that used for curve (1).

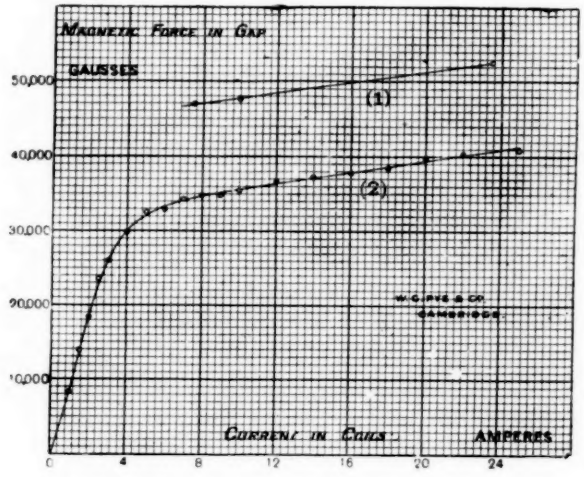

FIG. 1.—Field-strength for different values of the current

The determinations of 1903 were made by means of a ballistic galvanometer and a small coil which was suddenly jerked out of the magnetic field. Suitable mechanical arrangements were made to insure that the coil was properly placed between the pole-pieces. A standard of mutual induction from the Laboratory of Engineering was used to calibrate the ballistic galvanometer, and the current in the primary winding of this standard was measured by a good ampere-meter from the Cavendish Laboratory. I verified by tests that the value of the mutual induction marked on the standard was, at any rate, nearly correct. The small coil had a single layer of very fine wire; the diameter of the bobbin was carefully measured and a proper allowance was made for the

thickness of the wire. The current exciting the magnet was measured either by a good ampere-meter from the Cavendish Laboratory or by an instrument belonging to the Chemical Laboratory, which was compared with the Cavendish Laboratory instrument. I cannot now say which plan was adopted. Since the field increases very slowly as the current increases in the neighborhood of 20 amperes, moderate accuracy in the measurement of the exciting current suffices.

Those who have made similar measurements on large electromagnets with small pole-pieces and a narrow gap will understand that, although the tests are easily described, the experimental difficulties in the way of obtaining very precise results are considerable. All I can say at the present time is that I took all the precautions which I thought were necessary and that I should have felt disappointed if my results for a gap of 4 mm and for pole-pieces 7 mm in diameter with 20 amperes of exciting current were in error by as much as 5 per cent.

Purvis has throughout his work relied on my measurements of 1903. Since that date, however, one of the coils of the magnet has been damaged by overheating and has been rewound with a slightly smaller number of turns. The change in the number of turns is not sufficient of itself to account for the differences in the values of the magnetic force found in 1903 and in the measurements of 1912 which are described below. Defects may have developed in the other coils also, but they have not forced themselves upon the attention of those who have used the magnet.

In view of the criticisms of Cotton, I agreed, at the request of Purvis, to make a new set of measurements by the ballistic method. These were made in October 1912; the measurements were not so extensive as those of 1903, but are sufficient to settle the point at issue. The result is to show that the current of 20 amperes, which Purvis trusted to give him 39,980 gausses, at the date of the recent measurements only gave 28,700 gausses.

In the measurements of 1912, the ampere-meters were tested by aid of a standard resistance and a certified cadmium cell. The standard of mutual induction was one constructed at the Cavendish Laboratory under my supervision. The form was that

recommended by Searle and Airey,[1] and the coefficient of mutual induction (M) was calculated with great care by the formulae given by Searle and Airey from measurements made by myself. This standard was compared with one from the Engineering Laboratory and the value of M for the Cavendish Laboratory standard deduced from the value of M marked on the Engineering Laboratory standard was found to be in good agreement with that calculated from the formulae.

The bobbin of the coil used in measuring the magnetic field had a diameter of 0.500 cm and was wound with 15 turns of silk-covered wire 0.013 cm in diameter. The effective area was thus $\pi \times 15$ $(0.2565)^2$ or 3.1004 sq. cm. The coil was wound on an ivory bobbin. The coil was connected in series with the secondary coil of the induction standard and with a moving coil ballistic galvanometer. The coil was suddenly withdrawn from the gap of the magnet and the ballistic effect was observed. By comparison with the ballistic effect due to the reversal of a measured current through the primary coil of the induction standard, the value of the magnetic field was obtained.

The two limbs of the electromagnet were adjusted so that the pole-pieces were as nearly as possible symmetrically placed with regard to each other. The gap was set by aid of a metal distance piece 0.4 cm thick, so that it measured 0.4 cm in width when the magnet was excited with 20 amperes. The attraction between the poles with an exciting current of 10 amperes is sufficient to diminish the width of the gap by about 0.017 cm.

TABLE I

Exciting Current Amperes	Magnetic Force 1912 Gausses	Magnetic Force 1903 Gausses
4	23,900	29,800
6	24,700	33,600
10	25,800	35,400
15	27,800	37,300
18	28,600	38,400
20	28,700	39,700

Table I gives the values of the magnetic force found in the present measurements (1912). For comparison I have added the values found in 1903 for the same exciting currents, as read off from the chart which I made in 1903.

[1] *The Electrician*, December 8, 1905.

There is a slight discrepancy between the value 39,700 read off from the chart and the value 39,980 used by Purvis, but this may be neglected in the present discussion.

The magnet used by Purvis is shown in Fig. 2. It is constructed of a special mild steel and consists of a massive base carrying two limbs on which the coils are wound. Slots in the base allow the width of the gap to be adjusted. The limbs have a cross-section

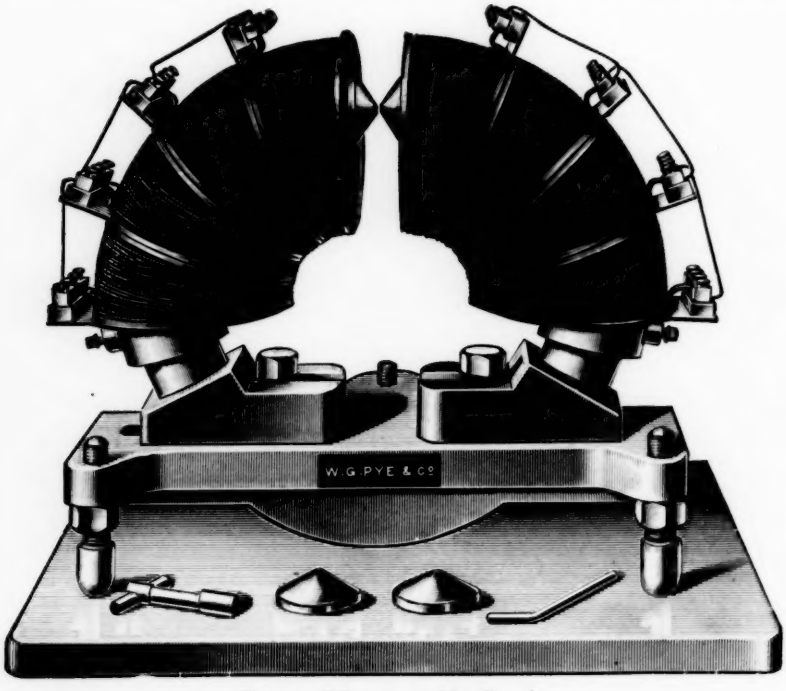

FIG. 2.—Magnet used by Purvis

of 50 sq. cm and the central line of each limb is part of a circle of 20 cm radius. The ends of the limbs are made truly plane and the bases of the conical pole-pieces are ground to fit them. The cones have angles of 120°. Each limb carries four coils, each originally wound with 280 turns of cotton-covered wire, 0.25 cm in diameter; the total resistance of the eight coils in series was about 3 ohms. The coils carry 20 amperes continuously without undue heating.

The magnetic forces obtained in 1903 with the pole-pieces mentioned above and with other pole-pieces exceeded the theoretical

maximum values deduced on the assumption that the pole-pieces were uniformly magnetized to a saturation intensity of magnetization of about 1600 C.G.S. It seemed probable that the magnetic force in the gap was due not only to the surface magnetism on the surface of the pole-pieces, but also to a volume distribution within the pole-pieces due to the non-uniformity of the magnetization which must occur in practice, the amount of magnetism per unit volume being:

$$\frac{dI_1}{dx}+\frac{dI_2}{dy}+\frac{dI_3}{dz},$$

where I_1, I_2, I_3 are the x, y, z components of the magnetization. Thus the fact that the values observed in 1903 were greater than the theory of uniform magnetization allows was not conclusive evidence that those values were erroneous. The circumstance led me, however, to investigate the magnetic properties of the steel of which the magnet was formed. Messrs. W. G. Pye & Co. supplied me with a carefully turned ring of the metal and I tested it for permeability (μ). The ring was wound with wire until no more wire could be wound on. As the magnetizing force reached values which are not often attained by the use of electric currents alone, it may be of interest to give the results.[1]

TABLE II

Magnetic Force Gausses	Magnetic Induction Maxwells per sq. cm	Permeability μ	Intensity of Magnetization I
1	950	950	75.5
2	5,190	2595	413
3	7,950	2650	633
4	9,680	2420	770
5	10,700	2140	852
7	12,160	1737	968
10	13,380	1338	1065
20	14,870	744	1182
30	15,600	520	1240
50	16,430	328.6	1305
100	17,460	174.6	1382
200	18,850	94.25	1485
400	20,380	50.95	1590
600	20,960	34.93	1621
800	21,400	26.75	1640

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CAMBRIDGE, ENGLAND

[1] These results were communicated two or three years after the 1903 tests to Professor Andrew Jamieson for a book on magnetism he was then writing, and a copy was preserved by Messrs. W. G. Pye & Co.

Minor Contributions and Notes

NOTE ON THE SPECTRUM OF THE ALUMINIUM ARC

In July 1909 Paschen[1] published measurements of the principal series in the aluminium spectrum. He gave the wave-lengths of four doublets corresponding in his series formula to $m=3$, 4, 5, and 6. The last-mentioned doublet falls within one of the aluminium bands and, as it is faint, is difficult to obtain and measure. Paschen puts a question mark after his determination but, as he gives only 0.06 Å.U. as the limit of error, it may be supposed that the uncertainty lies not so much in the measurement as in the identity of the line.

When Professor Hicks[2] applied his formula to this case, using the wave-lengths of the lines $m=3$, 4, and 5 to calculate the constants, he found that the calculated value for $m=6$ differed considerably from the measured value. By calculation he found $P_2(5)=5107.81$, $P_1(5)=5108.22$, while Paschen gives 5105.57 with the note "in a band, very uncertain, probably double." At his suggestion I therefore undertook to test this question, using a spectrograph with two calcite prisms.

The first photographs taken were of the aluminium arc in air at low pressures (from 2 to 20 cm of mercury), using an apparatus designed by Professor Hicks. It was thought that the principal series would appear better with the arc under low pressure. The apparatus used is shown in section in Fig. 1. The body of it consists of two cylindrical iron tubes, *C*, *D*, fitted at right angles. The arc is formed at the point of intersection of the axes of the two tubes. At the ends of the horizontal tube *D* quartz lenses were fixed, by sealing wax, so that a convergent or a parallel beam of light could be obtained at pleasure. This arrangement also

[1] *Annalen der Physik* (**4**), **29**, 625.

[2] *Phil. Trans. Roy. Soc.*, **212** A, 57; *ibid.*, **212** A, 33.

allowed the arc to be easily observed. The aluminium pole pieces were held in the specially shaped ends of the two iron rods, *A*, *B*. The rod *A* was screwed through a disk of iron in the tube *C*, and could be adjusted by the screw. The rod *B* passes up a glass tube slightly greater in diameter, which is fastened by sealing wax into a fiber disk, itself firmly sealing-waxed onto the lower end of the tube *C*. This and the screw on *A* had mercury seals. A wide piece of glass tube *E* was fitted as shown onto a rubber stopper fixed to the iron rod *B*. This tube served the purpose of a mercury reservoir. On exhausting the interior of the apparatus, through a small side tube not shown in the diagram, the mercury rose in the space between the rod *B* and the glass tube, thus serving as a manometer. The arc was struck by raising the rod *B* to touch the fixed rod *A*. The length of the arc was adjusted by means of the screw *F*. This adjustment was necessary owing to the expansion of the rods and the pole pieces.

FIG. 1

On the first photographs no trace of the doublet could be seen and it was thought that the band spectrum possibly obscured it. Previous work on this band spectrum had not quite resolved the doubt as to whether it was due to the aluminium itself or to the oxide. The effect of forming the arc in nitrogen between poles of pure aluminium, free from oxide, was therefore tried. Although it was not found possible thus to eliminate the band spectrum entirely, the latter was much less intense with the arc in nitrogen than in air. For this reason all other photographs were taken with the arc in

nitrogen. On these last photographs the doublet corresponding to $m=6$ was still invisible, but on some of them the doublets corresponding to $m=4$, 5 could be seen quite plainly.

It was then decided to vary the pressure and to observe carefully the changes in intensity of these doublets. The conditions which would be such as to make these most intense would probably at the same time be the best for showing any trace of $m=6$.

The doublets corresponding to $m=4$, 5 were found to increase in intensity with the pressure, and were therefore at their best with the arc under atmospheric pressure. (The apparatus used, as will have been observed, was available only for pressures equal to or less than atmospheric. It was later found possible, by lengthening

FIG. 2.—Aluminium arc at 10 cm pressure

the outer tube E, to increase the pressure up to nearly two atmospheres, but no further appreciable increase in intensity was observed.)

By using the arc in nitrogen at atmospheric pressure, a photograph was obtained showing what was most probably the required doublet, $m=6$. The dispersion was not sufficient to separate the components of the doublet, which thus appeared as a single line. The line was faint but quite measurable, its wave-length being 5107.5, a result agreeing as closely as could be expected with that predicted.

Apart from this result some other new and rather remarkable lines were observed on the photographs of the aluminium arc at low pressures. These formed three groups, two of which were much more prominent than the third, in the neighborhood of $\lambda=4250$ Å.U. These groups are not seen with the arc at atmospheric pressure except under prolonged exposures, and then only very faintly. With the arc at a pressure of about 10 cm they come out

extremely well. They are shown in Fig. 2. The individual lines in the groups do not vary much in intensity, and the heads, where several lines run together, stand out very clearly, except in the least prominent of the three groups. The groups show equally well with the arc in air, nitrogen, or coal-gas. The wave-lengths of as many lines as possible in the groups were measured approximately, using the iron spectrum as a standard, and are given below:

First Group	Intensity	Second Group	Intensity	Third Group	Intensity
4379.4	2	4287.4	9	4253.0	5
4375.5	2	4283.9	9	4251.1	5
4371.7	1	4280.4	9	4249.5	5
4365.4	2	4277.7	9	4248.1	5
4363.7	2	4275.2	9	4246.5	5
4361.7	1	4272.4	9	Several running to a head at	
Several running to a head at 4360.9	2	4271.0	7	4241.25	9
		4269.3	7		
		4267.5	5		
		4266.0	5		
		Several running to a head at 4260.05	10		

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NOTE.—The work described above was done in 1910, but was not sent to press until October 1912. I find that the groups of lines in the aluminium arc under low pressures have been measured recently by Miss Howson.[1] Miss Howson, using a Rowland grating, was able to obtain a much greater dispersion than was used in the above work, and measured many more lines of the groups.

ON THE EARTH LIGHT COMPRISED IN THE BRIGHTNESS OF THE MIDNIGHT SKY

In the *Astrophysical Journal*, May 1912, we find an interesting paper by Mr. Humphreys concerning which I should like to say a few words.

Mr. Humphreys explains that the light of the midnight sky seems to be composed of two parts, one reaching us directly from the stars, the other resulting from processes in the atmosphere, and

[1] *Astrophysical Journal*, **36**, 286, 1912.

that this latter part, termed earth light, is probably due, wholly or in part, to a permanent aurora. Mr. Humphreys then points out another possible cause of this earth light; the source is the continual bombardment of the outer atmosphere by materials of meteoric origin, i.e., by all particles picked up by the earth in its orbital motion.

I have shown[1] that, because of the number of shooting stars visible to the naked eye and the telescope, and the probable size of the particles producing this phenomenon, the reflection and scattering of sunlight by these meteoric particles ought not to be neglected. This should explain, at least in some measure, the difference that exists between the brightness of the midnight sky and the total light of all the stars together.

I did not take any notice of the proper light of the shooting stars, which Mr. Humphreys considered, and I feel obliged to give a reason for it.

Mr. Humphreys, starting from the estimated and generally accepted amount of meteoric material received by the earth, calculates the brightness that must result from it for the sky during night-time. But is it not possible that there is here perhaps a sort of syllogistic circle?

We really do not know the mass of meteoric material received by the earth, but only the brightness of the luminous processes produced by the shooting stars. Starting from that brightness, several learned men, more particularly Schiaparelli, have estimated the mass of the meteorites and have found it of the order of a gram. But the particles forming shooting stars have never been weighed. Stanislas Meunier even supposes that those particles have nothing to do with the meteorites picked up from the ground and coming from the aeroliths and that they are only gaseous bubbles.

The value of the mass which we have adopted may be very inaccurate. It is possible that the extrapolation of Stefan's law at a temperature as high as that of the stars is entirely wrong and that, in the case of shooting stars, the enormous energy produced by their arrival in the atmosphere is kept in the form of electricity, as the Marquis de Mauroy supposed it to be. In short, the

[1] *Bulletin astronomique*, January 1912.

relation between the mass of the shooting stars and their light may be very different from that generally admitted. But in any case, that mass should not be used to estimate the brightness of the midnight sky that must come from it.

The brightness of the sky due to the shooting stars should be estimated directly.

Moreover, if we compare the light of the shooting stars, visible to the naked eye, with that of all the stars together, it seems to be very feeble. It would be very interesting to know if the proportion is the same for the telescopic shooting stars. In any case if we limit ourselves to the shooting stars that are large enough to be seen individually, it appears that their total light can only be very faint compared to the total light of the fixed stars.

This remark does not at all lessen the interesting hypothesis given by Mr. Humphreys, for this theory may be applied to the particles that are far too small to produce visible streaks, the number and mass of which are quite unknown to us. It is possible, too, that the arrival of these particles in the atmosphere is quite sufficient to produce abundant ionization.

I only wish to explain that it is rather difficult to apply this theory to the shooting stars giving individual streaks, the only ones we know experimentally, and the only ones to which my calculations on the absorption and the scattering of the light through the meteorites may be applied.

P. SALET

OBSERVATOIRE DE PARIS

Reviews

Leçons sur les hypothèses cosmogoniques. By H. Poincaré. Rédigées par Henri Vergne. Paris, 1911. Pp. 294.

Researches on the Evolution of the Stellar Systems. Vol. II. By T. J. J. See. Lynn, Mass., 1910. Pp. 735.

Poincaré's last astronomical gift, his lectures on the hypotheses of cosmogony, are a fine testimony to his vigor as well as to the objectiveness and kindness of his mental disposition. The literature on cosmogony is very heterogeneous and in part impenetrable in consequence of prolixity, pretension, confusion, and general lack of mathematical control. Poincaré has gathered from this wild garden quite a multitude of fine fruits, a collection of ideas, of which perhaps everyone is likely to touch some part or other of the making of the worlds. He has not destroyed these ideas by criticism, but laid bare the core and even represented many of them in a clearer way than their authors. We must not find fault with him, when he takes notice chiefly of French authors with whom he is naturally most familiar, and in doing so overlooks some others. He quotes Kant, Laplace, Faye, du Ligondès, Bélot, See, Darwin, Lockyer, Schuster, Arrhenius. But he does not take notice, for instance, of the planetesimal hypothesis of Chamberlain and Moulton and of Emden's book on gaseous spheres (Gaskugeln).

The theories on cosmogony of the last decade are generally adverse to the nebular hypothesis of Laplace. Poincaré is no partisan of this opposition; he thinks, on the contrary, that the Laplacian hypothesis still, after some comparatively insignificant adjustments, is the best. The principal objection to the Laplacian hypothesis consists in the statement that the moment of momentum of a homogeneous sphere of the sun's mass, which has the diameter and period of revolution of Neptune's orbit, would be many times larger than the moment of momentum of the present solar system. To get rid of the objection, one has to suppose that the Laplacian nebula had from the beginning a very strong central condensation of almost the sun's mass, and that only about one-thirtieth of the whole mass expanded like an atmosphere around the massy central nucleus. When this fundamental supposition is introduced, it is possible to explain on the lines of Roche's deductions

and with casual application of tidal friction the origin of the solar system without undue difficulties.

The Kantian hypothesis takes as origin of the solar system a swarm of meteorites. The collisions of the meteorites produce in the end the formation of the sun and the planets and the regularity of their orbits. The Kantian hypothesis reappears in a form which is free from its original ill-treatment of the principles of mechanics, as well in the work of Mr. du Ligondès as in the planetesimal hypothesis of Chamberlain and Moulton. There seems to be no doubt that frequent collisions, which are accompanied by loss of energy, are actually able to mould a regular system from the primitive chaos of meteorites. But Poincaré finds a difficulty in the following consideration: Besides the collisions approaches occur between the meteorites, which give rise to deflections of their paths in consequence of their mutual attraction by gravitation. These approaches act like collisions without loss of energy. They are like the collisions of the common kinetic theory of gases. Therefore, if the approaches alone occurred and the collisions proper were excluded or negligible, the whole swarm would in the course of time become a sphere in a kind of adiabatic equilibrium. When a planetary system is to originate from the chaos, it is necessary, on the contrary, that the effect of the collisions proper, which are accompanied by loss of energy, preponderate and the gravitational deflections are comparatively insignificant. The approaches naturally are much more frequent than the collisions. Therefore Poincaré seems to fear the preponderation of their total effect. But G. H. Darwin has already shown how small the effect of the single approach is. The writer has convinced himself that the total effect of the approaches is also small compared with the effect of the collisions as long as the single elements of the swarm of meteorites have not become as large as planets. Therefore this scruple can be put aside.

The hypothesis of See also belongs to the group of modernized Kantian conceptions. After the central sun and the principal planetary nuclei arose from the swarm of meteorites, the totality of the remaining small masses forms a kind of resisting medium in which the larger bodies move. A resisting medium of density increasing toward the center diminishes, as Mr. See proves, the axes and excentricities of the orbits. In this way the smallness of the excentricity of the planetary orbits is explained. As to the satellites, Mr. See takes them as former small planets, which have been captured by the larger planets with the help of the resisting medium.

After all, the sympathies of the writer are with the modernized Kantian hypothesis. The planetary system shows a mixture of chance and order. The Laplacian hypothesis seems to call for a perfect regularity, whereas with the Kantian hypothesis the partly accidental appearances of the present system may be traced to the accidental constitution of the primitive meteorites.

Most of the modern cosmogonies venture even to enter into the former history of the chaos from which our solar system originated. In doing so, they are inspired by the charm which emanates from the photographs of spiral nebulae. The origin of spiral nebulae Mr. See explains by the approach and the gravitational uniting of two diffuse swarms of matter. Chamberlain and Moulton calculate the consequences of the approach of two suns; Mr. Arrhenius suggests a real collision of two suns, which, according to him, first gives rise to a nova, from which afterward a spiral nebula originates. For an explanation of the formation of spiral nebulae perhaps one should take more into account the fact brought forward by Mr. E. v. d. Pahlen, that the finest spirals of the sky agree remarkably well with logarithmic spirals (*Astron. Nachrichten*, No. 4503).

To all these authors the regular figure of the spiral nebulae seems the first indication of the regularity of a planetary system; the brighter patches of light in the nebulae appear to them as the nuclei of future planets. According to their common opinion, the solar system has originated from a spiral nebula.

To the writer it seems not very credible that the solar system has ever been a spiral nebula. It is well known that the spiral nebulae as observed by us have a diameter at least a hundred or a thousand times larger than the diameter of Neptune's orbit. If they had a mass of the order of the sun's mass, there would follow a density of the order of 10^{-15} to 10^{-18} of the density of water. A small density gives no difficulty in itself, but it is hard to suppose that matter of such tenuity should give a continuous spectrum with absorption lines, as it is shown according to Scheiner by the nebula in *Andromeda*, and, according to Fath, by some other spirals. Therefore it seems to follow that not only the diameter, but also the mass of spiral nebulae, is of quite another order of magnitude than those of the solar system, which implies that the solar system cannot have been a spiral nebula.

With his fascinating imaginative power Mr. Arrhenius conceives even a cyclic course of the world. Spiral nebulae become solar systems and extinguished solar systems are again by collision changed into spiral

nebulae. But a cyclic process is incompatible with Clausius' famous theorem of the caloric death (*Wärmetod*) of the universe. In fact Mr. Arrhenius supposes that this theorem does not hold, that the "deterioration" of energy, which takes place in the suns by the transformation of mechanic into thermal energy, is balanced by a corresponding "amelioration" of energy in the spiral nebulae. The nebulae lose indeed the quickest molecules, which escape the control of their gravitation. By this process the nebulae become cooler. Those escaped molecules which reach a certain sufficiently distant part of space, all move in the same direction. This is the transformation of irregular thermal agitation into regular motion, which is necessary to overthrow Carnot's principle. Nevertheless Poincaré—although he does not express himself very clearly on this point—seems *not* to believe that the caloric death is much detained by the foregoing mechanism. The writer shares Poincaré's opinion. Firstly, it is not proved that under reasonable suppositions the amelioration of energy in the nebulae is anything like equal in amount to its deterioration in the suns. Secondly, the molecules escaped from different nebulae will mix everywhere, and even without collisions constitute again an irregular motion. On the suggestion of Mr. Bestelmeyer the writer made some time ago the calculation given in the note below, which proves that the mean kinetic energy, i.e., the temperature of the mixture of escaped molecules, is *less* than the temperature of the nebulae from which they escaped. Therefore not even regarding temperature, the escape of molecules constitutes an exception to Carnot's principle. Up till now no really effective rescue from Carnot's principle seems to have been found. Nevertheless it cannot be pretended that a cyclic course of the world is impossible within exceedingly long periods, 10^{50} years, let us say. One must remember the various other reasons as exposed by Seeliger in his note, "Über die Anwendung der Naturgesetze auf das Universum" (München: *Sitzungsberichte der Bayr. Akad.*, 1909), which forbid the unrestricted application of Carnot's principle.

NOTE.—Suppose the distribution of velocities v of the molecules at a point near the outward limit of a nebula to be given by Maxwell's law (a^2 a constant):

$$e^{-a^2v^2}v^2dv$$

The mean kinetic energy or temperature T at this point will be:

$$T=\tfrac{1}{2}\frac{\int_0^\infty e^{-a^2v^2}v^4dv}{\int_0^\infty e^{-a^2v^2}v^2dv}$$

When the potential of gravitation at the same point is equal to k^2, all the molecules for which $v>k$ will escape. The final velocity of these molecules becomes: $w_1=\sqrt{v^2-k^2}$. Their final mean kinetic energy will be:

$$T'=\tfrac{1}{2}\frac{\int_k^\infty e^{-\alpha^2v^2}w_1^2v^2dv}{\int_k^\infty e^{-\alpha^2v^2}v^2dv}$$

or, by introducing w as independent variable:

$$T'=\tfrac{1}{2}\frac{\int_0^\infty e^{-\alpha^2w^2}w^3\sqrt{w^2+k^2}dw}{\int_0^\infty e^{-\alpha^2w^2}w\sqrt{w^2+k^2}dw}$$

By subtracting the temperatures T and T' and multiplying by the denominator, we get:

$$2(T-T')\int_0^\infty e^{-\alpha^2v^2}v^2dv\cdot\int_0^\infty e^{-\alpha^2w^2}w\sqrt{w^2+k^2}dw=\int_0^\infty\int_0^\infty e^{-\alpha^2(v^2+w^2)}v^2w\sqrt{w^2+k^2}(v^2-w^2)dv\,dw$$

Writing the double integral again with the notations v and w interchanged and taking the mean of both expressions, we get:

$$\tfrac{1}{2}\int_0^\infty\int_0^\infty e^{-\alpha^2(v^2+w^2)}[v^2w\sqrt{w^2+k^2}(v^2-w^2)+w^2v\sqrt{v^2+k^2}(w^2-v^2)]dv\,dw$$

$$=\tfrac{1}{2}\int_0^\infty\int_0^\infty e^{-\alpha^2(v^2+w^2)}v^2w^2(v^2-w^2)\left(\sqrt{1+\frac{k^2}{w^2}}-\sqrt{1+\frac{k^2}{v^2}}\right)dv\,dw$$

which is clearly positive. Therefore $T>T'$ Q.E.D.

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The Structure of the Atmosphere in Clear Weather. (A Study of Soundings with Pilot Balloons.) By C. J. P. CAVE. Cambridge University Press, 1912. 4to, pp. 144.

In this book are published in detail the data obtained in 200 pilot balloon soundings. The highest points to which the balloons were observed in these soundings varied from 1.0 to 18.5 km, and their mean height was 4.4 km. The data are also summarized, the classification being made for the most part with reference to the wind data themselves as defined in the introduction and further in chap. i. The five types of structure considered are: (*a*) wind in the upper air steady

with no increase in velocity with height; (*b*) wind in the upper air increasing sometimes to several times the gradient value but remaining more or less steady in direction; (*c*) wind in the upper air decreasing in velocity; (*d*) reversals or great changes in wind direction in the upper air; (*e*) wind in the upper air blowing away from centers of low pressure. Class (*e*) is subdivided into (e_1) upper winds between west and north, and (e_2) upper winds between south and west. Under the heading "The Wind in the Stratosphere" are discussed 12 soundings in which the balloons were observed to pass through the base of the "stratosphere." Eleven soundings are unclassified. Type (*b*) was observed 47 times, (*e*) 37, (*d*) 34, (*a*) 32, and (*c*) 27.

The classification used has the merit of being suggested by the data themselves. It is indefinite, as noted on p. 35, in that the height to which a sounding extends has possibly too much to do with its classification, e.g., if the sounding of April 13, 1907, had extended to 3.5 km only, instead of to 6, it might have been put into class (*a*) instead of class (*b*). This leads to the remark that one might read the book with a better understanding if the stratum referred to as the "upper air" and frequently used in defining the types of structure of the atmosphere had itself been clearly defined in chap. i or in the introduction.

One concludes in reading the book that the limits of this stratum vary with the height of the observation, and to a considerable extent with the type of structure. Sixty-five per cent of all observations fall below 4.4 km. In the different types 53, 79, 89, 68, and 51 per cent, respectively, of the observations fall below this average height of all soundings.

In view of these percentages, a classification based on the behavior of the wind in the first 5 or 6 km, suggested on p. 69, would not be so generally useful in these data as one based on the behavior of the wind in the first 3 or 4 km. In a continental climate, such a classification as the one used would probably be fairly definite if the lower 3 to 5 km of the atmosphere, depending on the season, were considered. This height could apparently be reduced by 1 to $1\frac{1}{2}$ km for insular climates.

The classification used has the further merit of bearing a fairly definite relation to surface pressure and temperature distribution. In the careful, systematic discussion of these relations in connection with the summaries of data and results in chaps. v and ix, a number of conclusions of much importance to meteorology are reached. The types of structure (*d*) and (*e*) appear of especial interest to the forecaster as well as to the dynamic meteorologist.

In type (*d*) the upper current is usually southerly and potentially, if not actually, warmer than the surface current, usually northerly—a condition nearly always accompanied by rain, frequently by thunderstorms. In the discussion of this type the direct statement of the conclusion that "the old idea of one current flowing close over another, and producing waves . . . . receives no support . . . . from actual observations" is a welcome one. This conclusion has been reached by other students of data, but the "old idea" still persists and is frequently used in the explanation of some cloud and other phenomena.

The conclusion pointed to by the observations of type (*e*), i.e., that a low-pressure area follows the direction of an upper wind blowing away from its center, is an important one from both the practical and the theoretical points of view. The same conclusion is indicated by the data of other observatories. The suggestion of a possible way in which the ascending air in the low-pressure area finds its way to the surface again in the high-pressure area is an interesting one.

Every student of dynamic meteorology sees the importance of free air observations to as great altitudes as may be reached; but, in the above and in other conclusions indicated in this "Study of Soundings with Pilot Balloons," are practical suggestions which should commend regular upper-air observation to the various weather services as a valuable aid to the forecaster in his work.

Chaps. ii, iii, and iv are devoted to discussions of methods of observing, the accuracy and checking of the data obtained, and the rate of ascent of rubber balloons—matters of great interest to the experimental meteorologist, possibly of less to the general reader.

Changes in the wind during the day and during consecutive days are considered in chap. vi. The wind in the "stratosphere" and the wind near the earth's surface receive attention in chaps. vii and viii, respectively. It is shown that in nearly two-thirds of the soundings the relation between the increase in velocity and the altitude up to 1 km is linear. Light variable winds are found in the "stratosphere," while in the region immediately below it are found the highest wind velocities observed.

In chap. vii or in an additional chapter the wind observations between the 1- and about the 4-km levels might profitably have been considered. The data from the soundings show a peculiarity in the lower as well as in the upper region of inverted temperatures or "stratosphere." All soundings considered, 87 per cent show a decrease in velocity with altitude somewhere between 1 and 4 km, 4 per cent show neither increase nor decrease for one or more kilometers in the same region, and only

9 per cent show an increase in velocity with altitude at all levels explored. Of those soundings that do not show a decrease in wind velocity with altitude, none reaches the 4-km level. Considering all soundings in the type of structure (*b*) that reach 5 km, it is found that in every case there is, somewhere between the 1- and 4-km levels, a decrease in wind velocity with altitude. The means of the wind velocities at the different levels in these soundings show no increase in velocity with altitude between the 1- and 2-km levels, a slight increase between the 2- and 2.5-km levels, and then no increase until the 4-km level is reached. This type of structure from its definition is the one least likely to show the phenomenon in question. These changes in wind velocity in the lower region of inverted temperatures are usually accompanied by greater or less changes in wind direction and also by changes in the other meteorological elements. A more or less regular increase in wind velocity with altitude is usually found between these two regions in which inversions of temperature are most frequently observed.

The discussion of the data is aptly illustrated with 47 figures and the tabular data themselves are supplemented with 35 pairs of diagrams showing the relations of wind velocity and direction to height in selected, typical soundings. These diagrams are accompanied by weather charts showing surface conditions.

The task of collecting these data and preparing them for publication comprises experimental work in the field in all seasons; the solution of some 8,000 triangles in connection with the reduction of the observations; the study of the data, their arrangement, illustration, and discussion; and finally the more mechanical work of proofreading and printing. In reading the book one is convinced that this task has been carefully performed and that the conclusions reached are well founded.

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Lehrbuch der sphärischen Astronomie. By L. DE BALL. Leipzig: Wilhelm Engelmann, 1912. 4to, pp. xv+387. $5.00.

According to the introduction, this work is intended, on the one hand, to serve as a book of reference for practical astronomers, and, on the other, to give to students the possibility of acquiring the knowledge absolutely necessary for a successful practical solution of the problems which arise in the realm of spherical astronomy.

As a prerequisite for the reading of the book the author mentions a

knowledge of the elements of analytical geometry, differential and integral calculus, and analytical mechanics. Series, interpolations, least squares, spherical trigonometry, and co-ordinates are treated in the first four chapters of the book. The fifth chapter contains a long and comprehensive treatment of the rotation of the earth. This is followed by chapters dealing with the old familiar subjects precession, nutation, aberration, refraction, parallax, proper motion, occultations, eclipses, etc.

A chapter on the formation of a fundamental star catalogue was evidently introduced as an afterthought, as it is numbered XIV*a*.

Brief sections are devoted to star streams and to the proper motion of our solar system.

Photographic methods and the fundamental equations connected therewith are utterly ignored.

In the purely mathematical part of the book a few numerical examples are given, but in the astronomical chapters illustrative examples are wholly lacking. The book contains comparatively little that is new, either in the line of material or in the method of presentation.

FREDERICK SLOCUM

Stereoskopbilder vom Sternhimmel. 1. Serie. Von PROFESSOR MAX WOLF. 4. Auflage. Leipzig: Verlag von Johann Ambrosius Barth. M. 5.

With the exception of pictures of the sun and moon astronomical photographs always look flat. From the nature of the case this must be so for the distances are so great that we can have no effect of perspective. But by properly combining photographs taken at suitable intervals of time the stereoscope introduces a perspective and gives an apparent solidity that must be charming to everyone who is interested in celestial objects.

This series of twelve pictures by Professor Max Wolf are very satisfactory both in choice of subject and in execution. They are as follows: (1) "A Variable Star"; (2) "A Planet with Moons"; (3) "A Planetoid"; (4) "A Meteor"; (5) "Perrine's Comet"; (6) "Perrine's Comet"; (7) "Perrine's Comet"; (8) "Proper Motion of a Fixed Star"; (9) "The Nebula of *Andromeda*"; (10) "The Great Nebula of *Orion*"; (11) "Surface of the Moon"; (12) "Surface of the Moon." The picture of *Saturn*, showing two of its moons, is particularly interesting.

We would suggest that these pictures might well find their way into the classroom, as few students will fail to be delighted with them.

W. D. MACMILLAN

Rocks and Their Origins. By GRENVILLE A. J. COLE. Cambridge: Cambridge University Press; New York: Putnam, 1912. 12mo, pp. vi+175. Figs. 20. $0.40.

This work, published as one of the long series of "Cambridge Manuals of Science and Literature," is a really excellent little book. Though a geological subject, it is intended primarily for those who are not specialists in geology, and as such necessarily presents the subject-matter in a simple, direct manner. But while declaredly a brief non-technical discussion, addressed to a general scientific audience, the character and treatment of the material selected are such that the more specialized student feels instinctively the complete command of the subject which alone makes possible such a succinct statement. There is so much meat condensed in these brief paragraphs that anyone interested in the subject finds himself continually calling for more and wishing that the treatment were fuller.

R. T. C.

The Work of Rain and Rivers. By T. G. BONNEY. Cambridge: Cambridge University Press; New York: Putnam, 1912. Pp. 144. Figs. 19. $0.40.

Of the various physiographic agents which fashion the face of the land, the most potent and universal is running water. How effective it is as a sculpturing agent is well told in this little volume. In five very readable and instructive essays the author has pictured some of the simpler phases of stream erosion, not by discussing the processes in textbook style, nor by elaborating principles primarily, but by describing and interpreting numerous concrete illustrations. The charm of the book lies in the abundant use of interesting examples from various parts of the world, though perhaps most largely drawn from the Alps and the British Isles. The last chapter, entitled, "Learning the Lesson," relates in graphic style how many centuries of philosophers came and went before the work of rivers came to be intelligently understood.

R. T. C.

NOTICE

The scope of the ASTROPHYSICAL JOURNAL includes all investigations of radiant energy, whether conducted in the observatory or in the laboratory. The subjects to which special attention is given are photographic and visual observations of the heavenly bodies (other than those pertaining to "astronomy of position"); spectroscopic, photometric, bolometric, and radiometric work of all kinds; descriptions of instruments and apparatus used in such investigations; and theoretical papers bearing on any of these subjects.

Articles written in any language may be accepted for publication, but unless a wish to the contrary is expressed by the author, they usually will be translated into English. Tables of wave-lengths will be printed with the short wave-lengths at the top, and maps of spectra with the red end on the right unless the author requests that the reverse procedure be followed.

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